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Physical-Chemical Treatment Technology

training manual

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PHYSICAL-CHEMICAL TREATMENT TECHNOLOGY

CLEAN WATER

TRAINING MANUAL

ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF WATER PROGRAMS

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PHYSICAL-CHEMICAL TREATMENT TECHNOLOGY

This course is offered for professional and technical personnel concerned with selection, design, operation, and evaluation of physical and chemical procedures for water pollution control and wastewater renovation.

ENVIRONMENTAL PROTECTION AGENCY
Office of Water Programs

TRAINING PROGRAM

January 1972

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FOREWORD

These manuals are prepared for reference use of students enrolled in scheduled training courses of the Office of Water Programs, Environmental Protection Agency.

> *Due to the limited availability of the manuals, it is not appropriate to cite them as technical references in bibliographies or other forms of publication.*
>
> *References to products and manufacturers are for illustration only; such references do not imply product endorsement by the Office of Water Programs, Environmental Protection Agency.*

The reference outlines in this manual have been selected and developed with a goal of providing the student with a fund of the best available current information pertinent to the subject matter of the course. Individual instructors may provide additional material to cover special aspects of their own presentations.

This manual will be useful to anyone who has need for information on the subjects covered. However, it should be understood that the manual will have its greatest value as an adjunct to classroom presentations. The inherent advantages of classroom presentation is in the give-and-take discussions and exchange of information between and among students and the instructional staff.

Constructive suggestions for improvement in the coverage, content, and format of the manual are solicited and will be given full consideration.

Joseph Bahnick

Joseph Bahnick
Acting Chief
Direct Technical Training Branch
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Environmental Protection Agency

TRAINING PROGRAM

Through the Water Quality Office, Environmental Protection Agency conducts programs of research, technical assistance, enforcement, and technical training for water pollution control.

Training is available at five installations of the Agency. These are: the National Training Center located at the Robert A. Taft Sanitary Engineering Center in Cincinnati, Ohio; the Robert S. Kerr Water Research Center, Ada, Oklahoma; the Southeast Water Laboratory, Athens, Georgia; the Pacific Northwest Water Laboratory, Corvallis, Oregon; and the Hudson-Delaware Basins Office, Edison, New Jersey.

The objectives of the Training Program are to provide specialized training in the field of water pollution control which will lead to rapid application of new research findings through updating of skills of technical and professional personnel, and to train new employees recruited from other professional or technical areas in the special skills required. Increasing attention is being given to development of special courses providing an overview of the nature, causes, prevention, and control of water pollution.

Scientists, engineers, and recognized authorities from other Agency programs, from other government agencies, universities, and industry supplement the training staff by serving as guest lecturers. Most training is conducted in the form of short-term courses of one or two weeks' duration. Subject matter includes selected practical features of plant operation and design, and water quality evaluation in field and laboratory. Specialized aspects and recent developments of sanitary engineering, chemistry, aquatic biology, microbiology, and field and laboratory techniques not generally available elsewhere, are included.

The primary role and responsibility of the States in the training of wastewater treatment plant operators are recognized. Technical support of operator-training programs of the States is available through technical consultations in the planning and development of operator-training courses. Guest appearances of instructors from the Environmental Protection Agency, and the loan of instructional materials such as lesson plans and visual training aids, may be obtained through special arrangement. These training aids, including reference training manuals, may be reproduced freely by the states for their own training programs. Special categories of training for personnel engaged in treatment plant operations may be developed and made available to the States for their own further production and presentation.

An annual Bulletin of Courses is prepared and distributed by the Water Quality Office. The Bulletin includes descriptions of courses, schedules, application blanks, and other appropriate information. Organizations and interested individuals not on the mailing list should request a copy from one of the training centers mentioned above.

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On October 4, 1971 at the San Francisco meeting of the Water Pollution Control Federation four Process Design Manuals were released by the Environmental Protection Agency Technology Transfer.

These included:

Upgrading Existing Wastewater Treatment Plants
    Contract No. 14-12-933, Roy F. Weston, Inc.,

Suspended Solids Removal
    Contract No. 14-12-930, Burns & Roe, Inc.

Carbon Adsorption
    Contract No. 14-12-928, Swindell-Dressler Co.

Phosphorus Removal
    Contract No. 14-12-936, Black and Veatch Construction Engineers

Recommendations contained in these or later releases by the Environmental Protection Agency supersede materials contained in this manual that are not consistent with these Design Manuals.

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PHYSICAL-CHEMICAL TREATMENT TECHNOLOGY

I INTRODUCTION

A Physical and chemical treatment operations have been an integral part of wastewater renovation since treatment began. Various operations have been used for initial and terminal cleanup, as well as within process of natural or engineered systems; biological treatment has received more attention as the workhorse of treatment. Operational compromise, established practices, unstable flow and apathy have combined to favor an empirical design basis that frequently does not favor process optimization.

B Today's problems in water renovation require a sophisticated integration of unit operations to include biological, chemical and physical unit operations in line with the wastewater characteristics and effluent quality sought at the optimum cost/benefit ratio. Several factors have forced increasing attention to the unit operations approach and physical-chemical operations in particular.

1 Water Quality Standards require increased activity in effluent quality control to meet compliance criteria.

2 Industrial operations favor larger production units resulting in more complex and varied components to be discharged as gaseous, liquid, or solid wastes. Conventional treatment is unlikely to be applicable for all possible discarded components.

a Certain toxic components may disrupt biological processes generally or downgrade them to unfavorable cost/benefit ratios.

b Substances relatively inert to biological processes may pass through the system with negligible effect upon the resistant fraction.

3 Biological processes have stressed oxidation and solids concentration. Recycle or feedback of various components to the effluent stream is receiving increased stress. Appropriate physical or chemical treatment favors take-out before, during, after, or in place of conventional treatment.

4 Once separate population or activity centers are losing, or have lost their isolation, the one-time permissible discharges are no longer satisfactory. Physical-chemical treatments are useful to:

a Upgrade existing treatment efficiency.

b To make the treatment more specific for a particular discharge.

c To remove components that commonly are not significantly removed by conventional treatment.

d Generally are more applicable for contingency use to protect existing plants and/or receiving waters.

e Are useful to broaden the spectrum of organic or inorganic components in the waste stream that may be effectively treated.

5 Cost per unit of benefit tends to increase as effluent quality requirements rise. This forces a re-evaluation of unit operations and the selection of those that are best adapted to a particular function under conditions favoring optimum effectiveness.

a Percentage treatment figures tend to be impressive, but the quality of the discharge is the real objective.

b The added increments of treatment increase complexity and degree of design and process control.

II COURSE OBJECTIVES

There are a number of "desired learning outcomes" common to this course. Each treatment operation has characteristics that are advantageous and others that are limiting in their applicability. Each situation differs in requirements that influence the balance of advantages and limitations. This course is intended for a unit operations approach to examine selected operations for purposes of selection, design and operational factors pertinent to their use as a guide in these and other treatment operations.

A Primary Learning Objectives

1 Review the basic theoretical concepts relative to a given unit operation and principle variables influencing its use.

2 Identify the variables most likely to influence design.

3 Recognize and evaluate the effects of conditional variables, human effects, and other non-theoretical influences that may require design modifications to assist functional efficiency.

4 To relate the situation, theory and experience background of the unit operation for completeness of design data under anticipated use. Are certain aspects vague enough to warrant pilot plant investigation? If so, what kind.

5 To participate in or to monitor experimental work related to design problems and to be considered in primary operational control technology.

6 To utilize information derived from theory, experience and laboratory or plant data in developing case situation solutions related to selection and design of treatment facilities.

B Secondary Learning Objectives

1 Selected unit operations will receive major attention during the course. Procedures used for these may be adapted for use in other situations. Certain operations will be discussed in lecture type presentations that indicate principle variables with little opportunity to perform detailed development.

2 The conduct of the course will be informal to provide opportunity for maximum participation of those present to question, comment and otherwise explore ideas that are pertinent to optimum consideration of the topics.

3 There are no universally "correct" answers. Possible alternative procedures will be explored on the give-and-take of class discussion to convert a given design into a functional facility. That which in the opinion of the group has answered most of the problems will be favored but the inquiry is more important than the answers.

III THE MEANING OF DESIGN

A The word "design" means different things to different people. Webster defines design as follows: "To creat, plan, or propose for a specific function".

1 The design procedure is subject to a variety of constraints such as economics, objectives, space, time, human factors (custom, activities, apathy, skills), and change.

2 The design procedure involves prediction of likely needs and the facilities to meet these needs with incorporation of a high degree of versatility to meet the needs for changing situations and requirements.

B Class problems will not be restricted to selection and sizing of equipment for operation. Alternate procedures will be explored in line with what ought to be done and what can be done in a given situation subject to the constraints of the immediate and forseeable future. Probable function is the objective to a greater extent than the facility.

ACKNOWLEDGMENT

This outline contains significant portions of a previous outline by F. Patrick Nixon.

This outline was prepared by F. J. Ludzack, Chemist, National Training Center,
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UNIT OPERATIONS IN WASTE TREATMENT

I INTRODUCTION

A Definitions

1 Unit operation[1] a particular kind of a physical change that is repeatedly and frequently used as a step in the process for industrial chemicals and related materials. Examples include filtration, evaporation, distillation, heat transfer, fluid transfer, sedimentation and mixing.

2 Unit process[1] a particular kind of chemical reaction and equipment to which the same basic designs and operation may be applied. Oxidation, coagulation, disinfection, hydrolysis and chemical absorption are common examples.

3 Process - a series of actions or operations conducing to an end. A continuing operation or treatment consisting of a combination of unit operations. For example, the activated sludge process includes mixing, fluid and gas transfer and clarification among unit operations; oxidation, hydrolysis and coagulation either biological or chemical among unit processes.

4 Wastewater treatment[2] any process to which wastewater is subjected to remove or alter its objectionable components.

a Wastewater treatment may also be defined as a series of unit operations designed to produce a product "clean water" from a raw material "waste water."

b Treatment is a means to renovate used water to meet a specific beneficial reuse requirement.

c Conventional treatment is commonly classified by stage or degree of treatment such as preliminary or pretreatment, primary, secondary, or advanced treatment. Processes such as activated sludge, trickling filtration or oxidation pond treatment are commonly used. Each of these can be more precisely described and better understood in terms of the unit operations involved.

d Unit operations for purposes of this outline include both "unit operations" (A. 1) and "unit processes" (A. 2) to distinguish unit process from the more generally applied term "process" which may include many unit operations or unit processes.

B Increasing stress on environmental quality means that wastewater treatment must be upgraded. Upgrading treatment means: removal of a larger fraction of conventionally removed components and removal of additional items presently not significantly removed by conventional treatment. This also means treatment of a larger fraction of collectable wastewaters for a greater variety of used water types and components for 24 hours per day, 365 days per year.

1 The unit operation concept tends to focus attention upon the specific components to be removed and upon fundamental units most suitable for that function. The unit operation approach offers a wider selection for design purposes than that available in empirical plant design. The treatment therefore may be more specific, better tailored to the situation and show a better cost/benefit ratio.

2 Implementation of treatment operations requires motivated and trained manpower. Personnel training along the unit operations route shortens the time and promotes better comprehension by focusing upon the unit operations or tasks most commonly used. Rotation among assignments is a smoother and progression more likely because the individual trained in unit operations tends to recognize familiar unit operations in the new assignment; his learning requirements consist of the differences, such as a different sequence of familiar tasks, a smaller number of new unit operations, and different handling techniques because of material or situation. Learning is split into fundamental units. Personal progress, job satisfaction, and competence increase with the recognition of proficiency of the smaller "bits."

C This outline considers selected unit operations of sanitary engineering(3, 4) and processes based upon them. Tables presented later summarize interrelations and the means whereby these are combined into processes or stages of treatment.

1 Unit operations are the fundamental "building blocks" of treatment.

2 Unit operations are the alternate routes to a given objective. Solids-liquid separations may be achieved by many different operations; some are favored in one situation, others limited by that situation.

D The following sections consider individual unit operations and their characteristics as guidelines for selection or design. These notes are general in nature and subject to the influence of waste characteristics, local conditions, practice, economics and water quality requirements of the situation. Each unit operation is characterized in terms of:

1 Favorable application factors

2 Limiting application factors that may encourage selection of an alternate operation for a particular situation.

II PHYSICAL UNIT OPERATIONS - SOLID-LIQUID SEPARATIONS

The separation of solids from liquid, or the reverse, is of primary importance to wastewater treatment. Various unit operations or adaptations of them to achieve this objective may be used to remove objectionable components, to protect process equipment, to simplify subsequent operations, to increase stability of process water, to make the water more amenable for treatment or to complete the process. Separations may be a part of pretreatment, an integral process step, or a means of upgrading process effluents. No single operation appears more frequently, in more numerous adaptations, at more stages in processing, and is more critical in product water upgrading than solids-liquid separation.

A Gravity Sedimentation

1 Favorable aspects: This unit operation is by far the least expensive and feasible route for a large variety of separations. May be adapted for separation of a variety of materials having a specific gravity sufficiently different from that of water and immiscible in it such as: High density sand, gravel or scale, moderate density organic suspended materials, low density floatable materials. Requires simple and generally available equipment. Operating variables are known and generally controllable to favor reliable treatment.

2 Limitations: Adversely affected by variations in wastewater characteristics and flow. Requires a moderately large capital, equipment and area investment. Sludge detention conducive to solids liquefaction and feedback. Affected by short circuiting, turbulence, distribution, temperature or density changes. Relatively slow operation in most situations.

B Surface Filtration

1 Coarse or fine screens

a Favorable: Inexpensive simple operation and equipment. Reliable removal of discrete solids larger than the screen openings. Equipment available and operating practice known. Simplifies subsequent operations. Low area requirement.

b Limitations: Susceptible to plugging, large quantities of wet, difficult-to-handle solids. Variable loading may result in operating and performance problems associated with higher loads.

2 Microscreens

a Favorable: Produces an effluent of low suspended solids (<10 mg/l) and low turbidity (2JTU) at low capital, operating time and area cost at rated loading. Simple operating requirements. Equipment availability good.

b Limitations: Poor tolerance for high suspended solids feeds (>50 mg/l). Tends to plug filter surface. Affected by changes in waste characteristics. Solids breakthrough at excessive loading.

3 Diatomaceous earth filtration

a Favorable: Produces a high quality effluent low in suspended solids and turbidity (0. 1 to 1. 0 JTU). Low area requirement. Pressure buildup rather than solids breakthrough warning of overloads.

b Limitations: High pressure drop through the filter; rapidly increases with solids loading. Tends to plug. Low output/sq. ft./unit time with high suspended solids feed.

4 Vacuum filtration

a Favorable: Suitable for treatment of a variety of solids-liquid concentrates. Large choice of filter media including string, coil, cloth (natural or synthetic) screens. Versatile in adaptability for varying conditions and loading. Low area requirement. High capacity per unit area.

b Limitations: Complex operation, high maintenance cost. Usually requires chemical coagulation or coagulant aids. High capital and operating cost. Requires frequent attention to maintain capacity during varying load and sludge characteristics. High cake moisture content produces a poor quality filtrate.

C Bed Filtration

Many options are available such as type of media (sand, coal, gravel, synthetics, etc.) size of media (from fine sand to rock or manufactured media) and flow direction (up flow or down flow, compressed or expanded bed). Fine media and downflow operation may resemble operational characteristics of surface filtration. Coarse media, multi media, expanded beds represent filtration in depth. In some situations such as trickling filtration, the process is largely a biological phenomena rather than intrinsically filtration.

1 Sand or single media filtration. Characterized by a high rate of head loss development with high solids loading.

a Favorable: High quality effluents produced. Increased solids, oxygen demand, and organism removals specially with low application rates. Beneficial for upgrading reasonably good quality treated effluents. Dependable polishing step. Simple operational control.

b Limitations: Large area requirement. Usually requires pretreatment for removal of most of the solids. High head loss development specially for high rate application. Usually an intermittent operation. Low capacity per unit time. Media replacement based upon incidence of "balling," backwash losses, deposition on the grains, and nature of feed stock contamination. Possible odor development. Backwash water may be voluminous and generally requires retreatment.

2 Soil percolation

a Favorable: Generally a dependable method of effluent disposal where land is available. Returns both water and wastewater nutrients to the food chain. Useful for land reclaimation purposes. Requires simple operation and low operational cost. Versatile for use with a wide variety of wastewater types.

b Limitations: Commonly limited with respect to application rates. Requires a large land area for intermittent operation. Capital cost primarily related to land area requirements. Disinfection commonly required. Good agricultural practice needed to support good engineering. A cover crop, tilling and drainage control generally required. Subject to seasonal, soil, and topographical factors. Odors and health hazards tend to produce a poor public image. Ground or surface water hazard potential.

3 Multi media filtration

The use of two or more filter media in which both size and density are variable makes it possible to distribute trapped particulates in a wide zone with respect to filter depth. Usually a larger sized lower density media are placed over a fine high density media. Larger particulates are trapped in the upper zone while the fine media upgrade effluent clarity. Head loss development occurs more gradually to permit longer runs of high product quality as compared with single media filtration.

a Favorable: Head loss distributed throughout the bed, builds up more slowly to permit higher rate and volume application. Dependable high quality effluent production. Generally high capacity characteristics.

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Capable of being tailored to fit a particular feed and effluent quality requirement.

b Limitations: Design generally requires more careful evaluation of feed and product quality requirements. Solids load and nature are critical. Requires more careful control during backwashing to make it a more complex operation than sand filtration. Intermittent operation. Media and equipment more expensive. Usually requires pretreatment. Backwash water requires retreatment--may require more backwash water or more time than for single media filtration. Media replacement may be higher.

D Pressure Floatation

1 The operation consists of aeration of part or all of the liquid flow in a covered tank to trap exhaust air and provide a controlled pressure rise. Under pressure more gas will dissolve than can be retained at normal pressures. Discharge of the pressurized liquid to the clarifying compartment permits release of excess dissolved gas. The released gas tends to associate with oil, scum and particulates to favor separation from water as a floatable concentrate. Variables include time pressure, turbulence, air-liquid-solid interface area and nature, and association tendencies in both pressure and clarifying compartments.

a Favorable

The floatation process is highly versatile for separation of oils emulsions or particulates. It may be used for thickening or clarification with or without conditioning chemicals such as surface active materials, coagulants or other separation aids. It is possible to employ higher loading and higher overflow rates than for sedimentation. A higher solids concentration factor may be achieved. More complete clarification of hard-to-separate materials is possible. Usually requires less area per unit of capacity.

1) Activated sludge concentration by floatation is becoming increasingly popular because the hydrated solids are amenable to the floatation process to a greater extent than for sedimentation.

2) Oil and surface active agents tend to be more completely separated by floatation to produce a better clarified product water.

b Limitations: Usually requires very careful design and operation for a specific situation. The complex operation is sensitive to feed stock variations. Generally more complex equipment requiring closer control. More amenable to moderately concentrated feeds. Thickening operations may require duplicate solids handling for removal of floatable and settleable fractions. The subnatant zone commonly has a high solids concentration requiring retreatment. Clarification commonly is improved by increasing feed stock concentration. More expensive in capital and operating cost than sedimentation.

E Centrifugation

The centrifuge has a long history for dependable separation of liquid-solid suspensions according to specific gravity differences. Solid bowl, basket, or disc type machines are available. Horizontal solid bowl units appear to have the greatest potential in sanitary engineering. Organic sludge from water and grit from organic sludge separations are attractive. Variables include feed rate, solids-liquid characteristics, feed concentration, temperature, chemical additives; machine variables include bowl design, rotational speed, contained volume, input, distribution and takeout mechanisms.

1 Favorable: Highly versatile; may be designed for high sludge concentration or high separation on a variety of feeds. High capacity-low area requirements. Low capital cost per unit of capacity. Capable of solids concentrations up to 30 to 35 percent with favorable loads and operation; continuous performance.

2 Limitations: High power requirements (~0.5 HP/gpm). Usually necessary to make a choice between high solids concentration and high solids recovery--unlikely to have both. Reduced feed

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concentration tends to reduce both concentration and recovery of centrifuged solids. Centrate generally requires retreatment. Requires suitable design for a particular function, material and flow and performs best at rated loading.

III CHEMICAL UNIT OPERATIONS

For purposes of this outline a chemical unit operation refers to a particular kind of chemical transformation of feed stock (I. c.). The transformations may be inseparably associated with both physical and biological changes, for example, hydrolysis, oxidation and disinfection are closely related to biological changes, while coagulation, flocculation are closely related to physical operations. These transformations may be natural in origin or induced by chemical additions. In a multicomponent wastewater the control of treatment largely is a compromise situation among operations of biological-chemical-physical natures, some favoring, some interfering, with the intended function.

A Neutralization

The combination of excess acids and alkaline materials to form a salt and water is a recurrent natural process called Neutralization. Among other components, organisms release both carbon dioxide (acidic) and ammonia (alkaline) which neutralize each other to form ammonium bicarbonate and water. Under certain conditions nature tends to inhibit itself where an excess of acid or alkaline materials are favored such as in low pH deep waters or high pH surface waters. Growth may become limited because of pressure retention of excess CO_2 or rapid assimilation of CO_2 respectively. This unbalance is unlikely to be as serious as that due to local discharge of acid or alkali released from manmade sources. Neutralization is a common requirement.

1 Favorable: Neutralization enhances the probability for biological and certain chemical transformations. Commonly reduces corrosivity of acid waters. Increases acceptability of acid or alkaline waters for beneficial reuse in water supply, recreation, wildlife, agricultural industry and esthetics.

2 Limitations: Generally high operating and control cost. May produce gross quantities of solids for disposal or increase the dissolved solids in the water. Requires close control to prevent excessive additions.

B Oxidation

The oxidation of organic waste components in water is a primary consideration in wastewater stabilization. This process is intimately linked with solids-liquid separation. For example, organic soluble compounds may be oxidized biochemically to form settleable agglomerates of cell mass, to removable gaseous CO_2 and to less reactable water. Nitrogen compounds may be converted to the oxidized state and reduced to less reactable and removable nitrogen gas.

1 The use of oxygen (aeration or surface oxygenation) from air is by far the most used unit operation for supplying essential oxygen for intermediate and terminal stabilization.

  a Favorable: Generally available, low cost. Necessary pumping, cleaning and transfer equipment available at reasonable cost. Moderate power cost. Transfer capability reasonably good. Dependable supply.

  b Limitations: Limited solubility of oxygen in contact with air. Large capital investment in tankage and space. Air solubility and transfer limitations generally mean a low to moderate rate process.

2 The use of commercial oxygen instead of air permits a five-fold increase in oxygen partial pressures.

  a Favorable: Higher oxygen partial pressures permit higher solubility of oxygen in water and greater oxygen transfer rate in high demand situations. More likely to maintain a higher residual DO in high rate situations, or through the clarifier stage. More complete stabilization possible in less tankage and/or time. High oxygen tension favors sludge oxidation--lowers solids accumulation.

b Limitations: Better design requirements necessary to maintain high oxygen use efficiency. More complex system, more costly. Covered tanks and oxygen production facilities nearby usually required to favor cost/benefit ratios. Requires better operational control.

3 Ozone is another form of oxygen used primarily for special purposes.

a Favorable: Ozone is used primarily for odor control because of its high oxidizing energy and high activity in water. Capable of reacting with components that may not react with oxygen under similar conditions.

b Limitations: Ozone (O_3) is a highly unstable compound. Generally cannot be stored or made in high concentrations. Usually requires formation on site and use in pretreated water. High unit cost. Complex control.

4 Chlorine is commonly considered for disinfection; disinfecting properties are inherently associated with oxidizing energy.

a Favorable: Commercially available chemical, control equipment available, operating controls generally known. High energy material. Relatively simple operation. Versatile material capable of use in a variety of situations. Cost higher than that for oxygen but has a greater reactivity for many beneficial operations. Rapid reaction in most situations.

b Limitations: Hazardous-nonspecific toxicity in air or water. Chlorine reaction produces HCl during reaction. Usually requires neutralization. Highly corrosive in water solution or wet gas. Certain components such as ammonia preferentially react with chlorine to cause high chlorine demands. Requires close control. Generally requires pretreatment to avoid excessive chlorine dosage.

5 Peroxy-acid oxidizing agents

Permanganate and dichromate are the most common peroxy-acids used in sanitary engineering. Permanganate is relatively pH independent, dichromate is an effective oxidant only under acid conditions. Both have high oxidizing energy for special purposes.

a Favorable: High oxidizing energy. Capable of being separated from product water. Adaptable for special requirements such as destruction of most organic materials or color. Permanganate may occur naturally in water and in excess its color is its own indicator.

b Relatively high cost per unit of oxidizing energy. Excess reagent contributes to poor quality water. Close control required. Commonly does not oxidize ammonia nitrogen. May require catalysis to reduce delayed reactions.

C Hydrolysis

The addition of water to split large molecules into two or more simpler substances is an inevitable part of biodegradation. Cell mass may be hydrolyzed to form smaller component parts that are partially oxidized to yield energy for building another crop of cells. The process will continue as long as oxidation energy is sufficient for growth. Treatment tends to produce a low energy discharged effluent in which hydrolysis and oxidation become lower rate operations - (stabilized).

1 Favorable: Items favoring hydrolytic cleavage (liquefaction) include high or low pH, hydrolase enzymes or other catalysts, high temperatures, low or negative oxidation reduction potential (low oxygen tension) or anything favoring introduction of water into a complex molecule.

2 Limitations: Any situation favoring resynthesis of hydrolyzed components into larger molecules reduces the net effect of hydrolysis. Algal photosynthesis, bacterial or plant growth, absence of toxic components, and favorable conditions for growth usually are associated with high rate hydrolysis in a high energy situation but growth may be the predominant reaction. Any situation favoring dehydration limits hydrolysis.

IV PROCESSES USED FOR THE REMOVAL AND DISPOSAL OF ORGANIC MATERIAL

Isolation and stabilization are the key factors in wastewater treatment. Unstable intermediates must be stabilized to be acceptable as gaseous or solid residues. Isolation refers to separation of gaseous and solids residues from the recombining media--water. It is not possible to isolate or to stabilize to "end" products--somewhere in time recycle will occur. Each treatment operation is intended to hasten recycle for beneficial use and delay other types of recycle.

A Table 1 summarizes the functions of various stages of treatment. Certain unit operations are repeated at each stage in a different manner.

TABLE 1

WASTEWATER TREATMENT STAGES

Preliminary or Pretreatment:

1. Removal of roots, rocks, rags
2. Removal of sand, grit, gravel
3. To "freshen" the wastewater by short term aeration, chlorination, grinding or otherwise protect and promote subsequent treatment

Primary Treatment

Removal of readily settleable or floatable components

Secondary Treatment

Conversion of soluble or colloidal components to removable form with partial stabilization in process (commonly biodegradation).

Advanced Treatment of Wastewaters

Biological chemical or physical treatment of used water to meet specific reuse quality requirements. May consist of general or specific item clean-up.

Solids Disposal

Nonpollutional takeout favoring conversion to stable residues and separation of gas, liquid, and solid phases.

B Tables 2 and 3 list selected unit operations and the stages or processes in which they may be used. Note that many of these may occur repeatedly and that there is the possibility of including one or more options in any given treatment process

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depending upon performance requirements and nature of the problem. These lists of physical (2) and chemical (3) operations are not complete. It is not likely that all of those listed may be included in any modification of a treatment facility. The problem is to select a series of operations suitable to meet the performance requirements of the situation at a favorable cost/benefit ratio.

C Several processes are possible for secondary treatment. Each of these have several modifications. The most common are based upon biological-physical unit operations. Chemical-physical operations may be used to upgrade the overall removal, or to remove specific components commonly not sufficiently removed by treatment. The same processes may be used for advanced treatment providing the degree of removal is upgraded on all components of interest to meet specific reuse requirements.

TABLE 2

UNIT OPERATIONS BY TREATMENT STAGE OR PROCESS - PHYSICAL TRANSFORMATIONS

Unit Operation	Stage or Process*								
	Pre	Pri	Sec	Adv	AS	TF	OP	SP	D
Fluid Transfer									
liquid pumping	x	x	x	x	x	x	x	x	x
mixing	x	x	x	x	x	x	x	x	x
sludge pumping		x	x	x	x	x		x	x
process residues-scum	x	x	x	x	x	x			
Gas Transfer									
into process-oxygenation	x		x	x	x			x	
stripping	x		x	x	x			x	
mixing	x		x	x	x			x	
Solids Transfer									
applied chemicals		x	x	x	x			x	
process residues	x	x	x	x	x	x		x	x
Heat Transfer				x				x	x
Solids-Liquid Separation									
coarse screening	x								
microscreening			x	x	x	x			
gravity sedimentation	x	x	x	x	x	x	x	x	x
filtration			x	x	x	x	x	x	
evaporation-drying				x				x	x
distillation				x					
floatation	x	x	x	x	x	x		x	
thickening		x	x	x	x	x		x	
centrifugation		x	x	x	x	x		x	
adsorption			x	x	x	x	x	x	
elutriation	x	x	x	x	x	x	x	x	x
flocculation		x	x	x	x	x	x	x	x

TABLE 3

UNIT OPERATIONS BY TREATMENT STAGE OR PROCESS - CHEMICAL TRANSFORMATIONS

Unit Operation	Stage or Process*								
	Pre	Pri	Sec	Adv	AS	TF	OP	SP	D
Oxidation Reduction									
wet combustion (biol-chem)	x	x	x	x		x	x	x	x
dry combustion				x				x	x
corrosion	x	x	x	x	x	x	x	x	x
bleaching (color removal)			x	x	x	x	x		
Disinfection	x	x	x	x	x	x	x	x	
Hydrolysis (liquefaction)		x	x	x	x	x	x	x	x
Solids-Liquid Separation									
coagulation		x	x	x	x	x	x	x	
precipitation		x	x	x	x	x	x	x	
ion exchange				x					
electrodialysis (phy-chem)				x					
complexation		x	x	x	x	x	x	x	x
assimilation (biol-chem)			x	x	x	x	x	x	
absorption (phy-chem)			x	x	x	x	x	x	
Neutralization		x	x	x	x	x	x	x	x

*Coding Tables 1 and 2

Pre - Preliminary or pretreatment stage

Pri - Primary clarification stage

Sec - Secondary treatment stage

Adv - Advanced treatment stage

AS - Activated sludge treatment process

TF - Trickling filtration treatment process

OP - Oxidation pond treatment process

SP - Sludge processing stage

D - Disposal stage (solids)

1 Activated sludge

This process is based upon a mixed fluid suspension of solids concentrates from previous operations and raw wastewater in the presence of excess oxygen to rapidly stabilize the incoming pollutants by biological growth, transfer to the solids phase, agglomeration and solids liquid separation.

a Favorable: Versatile process capable of being adapted to high performance on most types of organic contaminants. Generally capable of high efficiency in stabilization and clarification. Lower tankage and area requirements than for most biological processes. May be modified to achieve high removal of nitrogen phosphorus and solids. Adaptable to a wide range in removal efficiency.

b Limitations: Requires close control of load ratios and operating conditions. High oxygen requirements. Subject to upset by qualitative and quantitative shock loads. Unmodified process commonly shows poor removal of nitrogen and phosphorus. Subject to the variations of characteristic of biological treatment. High operating cost.

2 Trickling filtration

Employs an attached media of sewage slimes on the support surface for transfer and stabilization of organic pollutants in the influent.

a Favorable: Versatile process capable of being adapted for intermediate performance on most types of organic waste. Low operating cost. Adaptable for a fairly wide range of removal on substances showing good solids transfer efficiency.

b Limitations: High capital cost for land and tankage (rock or slag). High pumping cost on manufactured media. Generally not amenable for coagulation and clarification. Fewer operating controls possible. Subject to the variations characteristic of biological treatment even though it may not be as noticeable due to generally turbid effluents.

3 Oxidation ponds

Employs natural purification phenomena of sedimentation, aerobic and anaerobic degradation, algal photosynthesis usually in a sacrificial pond or series of ponds.

a Favorable: Capable of high treatment efficiencies with low operational cost. Adaptable to low or high removal efficiencies depending on land and capacity or time availability. Useful on a wide variety of wastewaters. Land is available for upgrading treatment and other uses as needed.

b Limitations: Generally limited to application where land costs are low. Subject to poor performance during ice cover, overloads, spring warmup and unexpected boil-up. May be an odor nuisance at times. Generally a low rate process with poor solids recovery characteristics. Appears to have a tendency to poorer performance after several years of operation.

4 Physical chemical treatment operations

Physical chemical treatment by lime precipitation and activated carbon adsorption is becoming recognized to an increasing degree.

a Favorable: Is a versatile process capable of being adapted to very high degrees of treatment on a variety of wastewaters. Recovery of added lime and regeneration of spent carbon by controlled incineration permits chemical reuse and reduces solids disposal. Relatively low capital costs and space requirements. Capable of application over

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wide flow variations with dosage and regeneration time control. Freedom from toxic effects.

b Limitations: Generally higher operating cost. More complex process requires precise operational control. May require pretreatment. Chemical reuse almost mandatory to limit solids disposal requirements. Operating history for wastewater applications scant.

D Sludge Processing or Disposal Routes

1 Wet combustion by aerobic biological processes

Activated sludge, trickling filtration and oxidation ponds involve a certain amount of processing and disposal of solids to a degree limited by the amount of carbon dioxide and water formed in process. Aerobic sludge digestion accentuates solids disposal.

a Favorable: Generally a conventional bio-chemical process using established procedures. Time, oxygen supply and favorable conditions are basic requirements. Versatile for a variety of wastes. Generally capable of a high degree of stabilization.

b Limitations: Process limited to a residue solids level containing about 40% volatile content (10 to 20% of the feed volatile solids). High liquid recycle of N, P, and solids content. Generally a long term operation. Process interference serious for low temperatures, toxic agents, or unfavorable pH. Generally produces a low concentration sludge (∿ 2%).

2 Wet combustion--elevated temperature and pressure

Wet combustion of organic wastes at various pressures in enclosed vessels with liquid temperatures of 350° F or above have been effective for separation of a highly stable mineralized ash.

a Favorable: Capable of producing an easily separated high-mineral ash. Rapid process low area requirements, low solids disposal volume.

b Limitations: Requires complex equipment and high heat requirements. Good control essential. Residual liquid has a high color and contaminant level.

3 Anaerobic digestion

This process is both a sludge conditioning and a solids separation process. Sludge residuals after digestion are more concentrated in solids content and decreased in volume and mass due to escape of methane and carbon dioxide gas or elutriate.

a Favorable: Versatile and dependable process of organic stabilization for suitable loading, mixing and temperatures. Low cost operation. Produces a usable product gas. Residual solids relatively stable, improved in concentration, and drainability.

b Limitations: Capital costs relatively high for space and tankage. Susceptible to shock loading, temperature changes, poor mixing or toxicity. Once upset--it requires appreciable time and effort to restore good performance. Recycle liquids are high in dissolved and suspended solids; are difficult to treat.

4 Drying and incineration

Many modes of drying such as drying beds, land spreading, flash drying are possible with wet sludge. Incineration in a fluidized bed, rotary kiln or multiple hearth are used. The multiple hearth is one example of drying and incineration.

a Favorable: Dependable, versatile operation for thick sludges where heat release is close to heat requirements for water evaporation and temperature rise. Can be controlled to produce clean stack gases and stable mineral solids residue. Rapid process. Low area requirements. Control techniques well established.

b Limitations: Solids feed of low heat and high water content may require excessive auxiliary fuel cost. Generally requires stack gas reburning and solids recovery to meet air quality requirements. Generally costs about $50 plus per ton of dry solids for operation. Requires close control of feed, burner temperature and other operating variables.

5 Wet disposal of sludge

Application of wet sludge to spoil areas, stripped terrain, farm or marginal land has been common practice for a long time. Piping instead of truck hauling is receiving increased consideration to extend the disposal area.

a Favorable: Costs of disposal may be reduced by avoiding costly drying operations. Pumping of wet sludge is more economical than hauling. Possibilities for use of the organic and water for reclamation of waste land is attractive as a means of recycling the wastes into the food chain. Isolation possibilities are improved by remote application from population centers.

b Limitations: Good engineering and farming practice are required. The local residents do not appreciate receiving waste materials from elsewhere unless practice and public relations are top rate. Possible hazards from surface ground water and air pollution dim the good neighbor policy.

ACKNOWLEDGMENT:

This outline contains appreciable material from a previous outline by F. P. Nixon.

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LABORATORY EQUIPMENT AND INSTRUMENTATION

I INTRODUCTION

The purpose of this outline is to acquaint the trainee with the fundamental and advanced types of equipment required to equip a treatment plant laboratory. Some consideration is also given to layout (design) of the laboratory.

The cost of furniture and analytical hardware is also discussed.

II ANALYTICAL TESTS AND EQUIPMENT

A variety of analytical tests are used to define a) the quality (strength of raw sewage; b) efficiency of various stages of treatment; c) completeness of treatment; d) industrial components.

A The tests required in any given treatment plant will vary depending upon

1 The capacity of the plant

2 The type of treatment

3 Industrial components

4 Other factors

B Some analytical tests are common to all treatment plants, but other tests are performed only as predicated by local conditions.

C The following tables summarize the tests used in treatment plant operation and the equipment needed to perform the test. (Tables 1, 2, 3)

Table 4 indicates the cost of various pieces of hardware as detailed in Tables 1, 2 and 3. Costs shown are maximum expected costs as of 1968.

Table 1

COMMON TESTS FOR STP OPERATION

Dissolved Oxygen	DO Probe	(g)
BOD	DO Probe Warburg Apparatus* Field (Hach) Units	(g) (G)
COD	Technicon*	(G)
pH	pH Meter	
Solids	Analytical Balance	(g)
Suspended, Dissolved	Drying Oven	
Settleable, Volatile	Muffle Furnace	
Total, Fixed		

g - ordinary glassware
G - specialized glassware
* - in special circumstances

Table 2

FREQUENT TESTS FOR STP OPERATION

Nitrogen Compounds	Kjeldahl Digestion	(G)
Organic N Ammonia N Nitrite N Nitrate N	Spectrophotometer	
Phosphorus Compounds	Spectrophotometer	(g)
Organic P Ortho P Poly P		
Fats, Grease, Oil	Analytical Balance	(G)
Conductivity	Meter	(g)
Minerals		
Chlorides Alkalinity, etc.	(G) Meter or Probe	(g)
Detergent Materials (MBAS)	Spectrophotometer	(G)

g - ordinary glassware
G - specialized glassware

Table 3

INFREQUENT (ADVANCED) TESTS FOR STP OPERATION

Sludge Volume Index		(G)
Grit		(G)
Volatile Acids	Meter	(G)
Gas Tests	Orsat Apparatus	(G)
CO_2		
CH_4		
Chlorine	Amperometric Titrator	
Demand		
Residual		
Total Organic Carbon	Combustion-IR	(G)
Heavy Metals	Atomic Absorption	(g)
Regulator Programs*	Technicon Apparatus	

g - ordinary glassware
G - specialized glassware
* - Regional plants, requiring multiple testing

Table 4

MAXIMUM COSTS OF ANALYTICAL HARDWARE

(1) Dissolved Oxygen Probe	$ 500
(2) Analytical Balance	1,000
(3) Spectrophotometer	2,000
(4) pH Meter	500
(5) Conductivity Meter	300
(6) Kjeldahl Digestor and Dist'n App.	1,000
Amperometric Titrator	400
Orsat Apparatus	200
Total Carbon Analyzer	6,500
Atomic Absorption	9,000
Technicon Analyzer	8,500
(7) Drying Oven	500
(8) Muffle Furnace	600
(9) Water Still	750

III LABORATORY DESIGN AND FURNITURE

A There is no universal floor plan for laboratory design but there are certain design conventions that should be observed.

1 Analytical balance should be isolated and shock free.

2 Expensive electronic equipment should be isolated or remote from fume-producing operations.

3 Ventilating hoods should be provided for fuming, digesting, and hazardous operations.

4 Desk work area should be available.

5 All foreseeable utilities should be built in during construction of laboratory.

6 Electrical capacity of laboratory should anticipate much more than initial requirement; regulated voltage to electronic equipment is desirable.

7 Adequate storage for samples should be provided outside laboratory.

B Area of laboratory and lineal feet of bench space is determined by size of plant, number of different tests to be run and final choice of equipment.

Costs of bench space runs about $160 per lineal foot for two-sided furniture (island or peninsula) and $120 per foot of wall-type bench (one side).

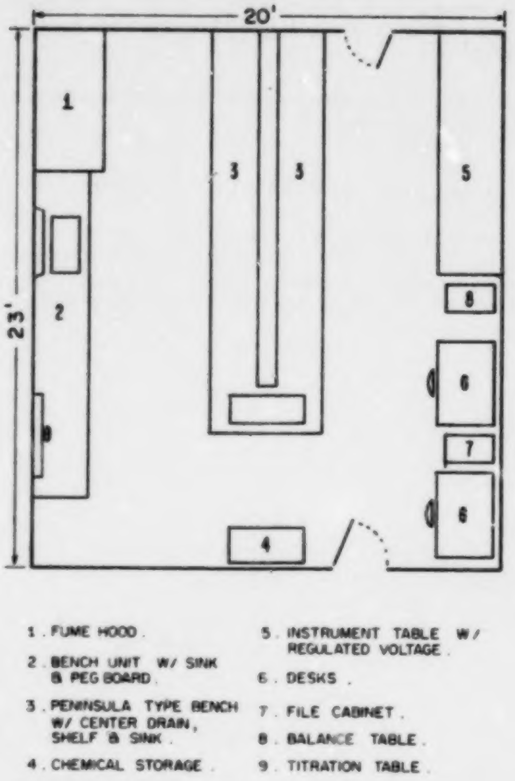
C An average laboratory, as shown in Figure 1, would cost as follows:

Bench space	$6,500
Desks and other furniture	500
Glassware	1,000
Analytical equipment (Items 1, 2, 3, 4, 5, 6, 7, 8, 9 from Table 4)	7,150
Wall cabinets, pegboard and miscellaneous	1,500
	$16,000 plus

D Floor plans and cost figures in this outline are given as examples and approximations. They should not be considered as "magic numbers"!

Figure 1

SAMPLE LAB.


20'
23'
1
2
3
3
4
5
6
6
7
8
9
1. FUME HOOD.
2. BENCH UNIT W/ SINK & PEG BOARD.
3. PENINSULA TYPE BENCH W/ CENTER DRAIN, SHELF & SINK.
4. CHEMICAL STORAGE.
5. INSTRUMENT TABLE W/ REGULATED VOLTAGE.
6. DESKS.
7. FILE CABINET.
8. BALANCE TABLE.
9. TITRATION TABLE.

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This outline was prepared by R. C. Kroner, Chief, Physical and Chemical Methods Section, Division of Research, Analytical Quality Control Branch.

THERMAL POLLUTION FROM NATURAL CAUSES

I INTRODUCTION

Although the term "pollution" is almost universally reserved for use in describing the results of man's activities, at times it can also define adverse environmental effects from other causes. Adverse thermal effects from natural causes have been observed since the first man appeared on the earth. If one accepts the biblical story of Adam and Eve, he could easily imagine Adam, on a hot summer day, telling Eve how difficult it was to work in the extreme heat, or in wintertime, the two of them huddling together for added protection from the cold.

In this outline, consideration will be given to the natural thermal sources and how they may affect the aquatic environment.

II NATURAL HEAT SOURCES

A The energy budget - as related to a water mass, the energy or heat budget is frequently expressed as: (Randall, 1962):

$$Q_t = Q_s - Q_r - Q_b - Q_h - Q_e + Q_v$$

where Q_t = increase of energy stored

Q_s = solar radiation incident to water surface

Q_r = reflected solar radiation

Q_b = net energy lost through long-wave radiation

Q_h = conduction loss to atmosphere

Q_e = evaporation heat loss

Q_v = advective heat loss or gain

This is shown schematically by Figure 1.

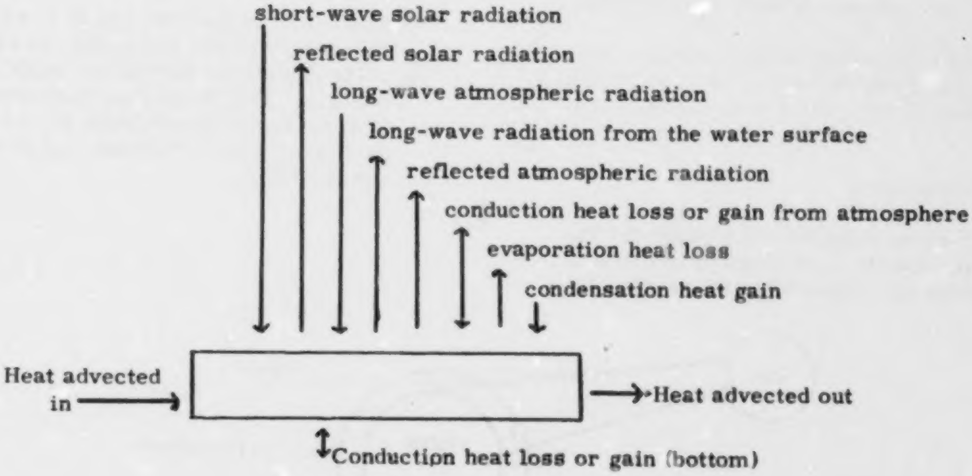
short-wave solar radiation
reflected solar radiation
long-wave atmospheric radiation
long-wave radiation from the water surface
reflected atmospheric radiation
conduction heat loss or gain from atmosphere
evaporation heat loss
condensation heat gain
Heat advected in
Heat advected out
Conduction heat loss or gain (bottom)

FIGURE 1

HEAT FLOW - RELATED TO WATER MASS

Although the energy budget equation is used as a base for predicting thermal pollution, at this time we will use the schematic (Figure 1) only as a means of identifying heat sources which may affect the environment.

B Volcanic Heat

Volcanic heat or heat from the earth's core may contribute considerable thermal energy to the aquatic environment. This heat is, however, usually confined to areas of hot springs and volcanos.

Some of these areas have become famous as resort areas and as such the volcanic heat in the environment is not considered pollution even though this heat may cause considerable deviation from the norm.

Studies of the aquatic biota in Yellowstone National Park have revealed some very definite variations from the normal. It is highly likely these forms have adapted to their "hot water" environment over a period of many thousands of years.

Although some proposals have been made to tap heat from these sources, until this time man has not made any significant alteration in the release of volcanic heat from the earth's core into the habitable environment.

In Figure 1, this heat source is shown as heat advected in by the hot water flow or by heat conduction directly from a stream or lake bottom.

C Solar Radiation

Short-wave radiation received from the sun is equal to 1.95 langleys per minute, of which approximately 40% reaches the earth's surface on an average of about 8000 calories per square meter per minute. The balance of radiation received from the sun is either reflected or absorbed by the atmosphere. Approximately 45% of the total received (0.88 langleys) is reflected back into space by the atmosphere. The atmosphere absorbs about 15% of the total (0.29 langleys). This latter helps to maintain atmospheric temperature and promote its circulation.

Although a total of 19,500 calories per square meter per minute reaches the earth with the sun directly overhead, the amount of this short-wave radiation which reaches the surface to be absorbed by a water mass is affected by:

1 The duration of sunlight per day, which is a factor of season and latitude.

2 The elevation of the sun. When the sun is directly overhead, its rays have the least distance to travel through the gas molecules making up the atmosphere. As the sun moves from the vertical this path increases (Figure 2) permitting greater absorption and scattering of the solar radiation by gas molecules in the air.

The result of phenomenon is to alter the rate, throughout the day, at which solar radiation reaches the earth's surface. The function of this change is approximately parabolic as shown by Figure 3 for a selected day at 45 north latitude.

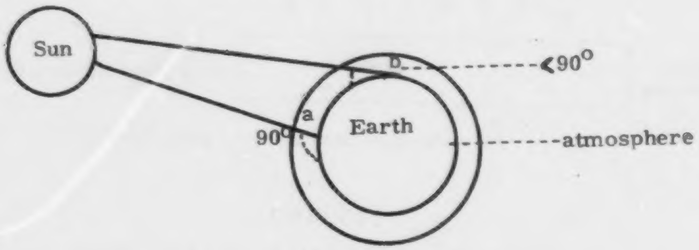

FIGURE 2

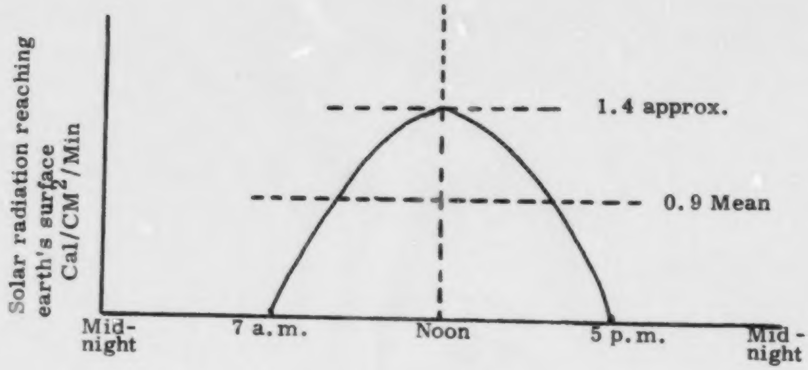

FIGURE 3

3 Cloud cover affects amount of energy reaching the surface because of absorption and scattering of the radiation in and by the water molecules.

4 In addition to direct sunlight the surface of a water mass also receives skylight radiation from sunlight that has been scattered by the atmosphere. This factor becomes more important in higher latitudes where the angle of the sun from the vertical decreases the amount of direct solar radiation and increases atmospheric scattering.

5 The reflective condition of the water surface, for example, calm, smooth surface or windswept waves is another important factor because as much as 2 to 50% of solar radiation reaching the water surface will be reflected from the surface depending upon surface conditions.

D Long-wave Radiation

Short-wave solar radiation absorbed into the atmosphere is altered to long-wave radiation in which form it may reach the water surface to be absorbed. Likewise long-wave radiation is lost from the water mass into the overlying air. Whether or not the long-wave radiation results in a net gain or loss of heat in the water mass is dependent upon temperature of the atmosphere, the water, and humidity.

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THERMAL POLLUTION RESULTING FROM MAN'S PHYSICAL ALTERATIONS OF THE ENVIRONMENT

I INTRODUCTION

Heat as a pollutant has been shown to have numerous adverse effects on water and the aquatic environment. Because of these effects, we should examine activities of man that may tend to change the environment in such manner as to affect the natural thermal regime of our waterways.

II RESERVOIR CONSTRUCTION

Reservoir construction has long been considered as an environmental change which affects the aquatic environment. This affect may take one of two routes to alter the downstream thermal regime.

A Bottom withdrawal of cold water causing a somewhat lower stream temperature than normally experienced during the summer months. The solar energy absorbed by the water mass is retained within the reservoir in the upper layer or epilimnion. Often this heat energy promotes algal blooms. During the die-off period, the dead algal cells settle to the thermocline and decompose. In some instances, this decomposition produces hydrogen sulfide which, if discharged to a stream, will result in a fish kill.

B Surface discharge from reservoir releases the epilimnion waters which, during transit through the reservoir, have stored solar energy in the form of heat. The discharge thus elevates downstream water temperatures.

Whether or not either of these conditions will adversely affect the downstream ecology can only be determined on a case by case basis and evaluation of the environment and water use.

Heat storage is frequently shown by the equation:

$S = I - O + R \pm C - E$ Where:

S = heat storage in reservoir

I = heat in inflow waters

O = heat in outflow

R = net energy absorbed from radiation

C = sensible heat exchange

E = evaporation heat loss

Most of the heat entering the reservoir does so as either advected heat in the inflow or from radiation with radiation usually being the greater. This can be readily seen by analyzing the difference in surface area (stream surface/reservoir surface) open to the sun as a result of the impoundment. Inasmuch as a mean rate of approximately 8000 to 9000 calories per square meter per minute reaches the water surface during daylight hours, considerable energy can be added to the water mass because of the increased water surface exposed. If alternate sites are available, the impoundment area should, if possible, be oriented to minimize absorption of solar radiation.

III LOGGING PRACTICES

Logging in such manner as to completely expose a stream to solar radiation can add considerable heat to the flowing water. This can best be shown by an example problem.

Assume an area to be logged will remove the shade and completely expose a stream for a distance of 1000 feet. This small stream has an average velocity of 0.5 feet per second.

Incoming radiation is 1.4 langleys per minute and the albedo is 0.02. Find the energy added to the stream as a result of shade removal. Neglect change in long-wave radiation, sensible heat exchange, and evaporation. Then:

$S = R - (R_s - R_f)\, t$ where:

S = additional heat stored in the water mass

R = net energy absorbed from radiation

R_s = short-wave solar radiation

R_f = the reflected solar radiation

t = time of exposure to sun's rays

$R_f = aR_s$

a = albedo (reflectivity of the water surface)

$$S = 1.4 \frac{Cal}{CM^2\ Min} - \left(1.4 \frac{Cal}{CU^2\ Min}\right)(0.02)$$

$$\left(\frac{1000\ ft\ sec}{0.5\ ft}\right) \left(\frac{Min}{60\ sec}\right)$$

$$S = \left(1.37 \frac{Cal}{CM^2\ Min}\right) (33.3\ min)$$

$$S = 45.7\ calories/CM^2$$

Thus, in this short stretch each centimeter of stream width will absorb more than 45 calories. If the stream is shallow, say an average depth of about 4 inches, the water temperature would rise on the order of 4.5° C or 8.1° F.

Although the problem was simplified somewhat by ignoring sensible heat exchange, long-wave radiation and evaporation, an error of sufficient significance was not introduced to invalidate our result. It becomes apparent that serious consideration should be given to protecting water quality by leaving vegetation along stream banks to shade the water surface from the sun's rays.

IV IRRIGATION RETURN FLOW

It has been pointed out the effect to be expected when water is diverted for irrigation. In instances of ridge and furrow irrigation, water is exposed not only to the heating caused by direct solar radiation, but also by sensible heat exchange from the soil of solar energy absorbed by the earth prior to application of irrigation water. In this case, however, evaporation becomes a very significant factor in helping to reduce the amount of heat stored in irrigation return flow waters. In the western United States where irrigation is widely practiced, elevated stream temperatures have been frequently observed.

V SUMMARY

Man can and does alter the physical environment in such manner to change the thermal regime of the aquatic environment.

He should recognize the effects of these changes and, where possible, their occurrence.

In those instances where alteration of water temperatures is unavoidable, such as might occur by construction of a reservoir, the dam should be designed to permit management of discharges in a manner to minimize adverse thermal effects.

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SECTION II THERMAL POLLUTION

	Outline Number
Industrial Sources of Thermal Pollution	6
Data Requirements, Field Studies, and Instrumentation for Temperature Prediction	7
Summary Outline of Current Theories Relating to Temperature Prediction in a Body of Water	8
Thermal Pollution Control Methods	9

INDUSTRIAL SOURCES OF THERMAL POLLUTION

I INTRODUCTION

The utilization of water by man is as old as man himself. This life-giving, universal solvent has many uses. It can be used for drinking or to carry away sewage wastes. A river may be used for transportation, recreation, food production (for fish habitat) or for waste disposal. These uses of water for man's benefit may be good but the result is a complex problem.

Competition between water uses is keen and growing intensely with the rapid growth in water demand. It is estimated that the nation's dependable continuous water supply is only 850, 000 cubic feet per second, an amount which will be equaled by the demand by 1980. This makes it necessary to manage the resource for multiple use. Antagonistic uses must be resolved to obtain maximum resource benefits.

Heat discharged to a stream conflicts with such other uses, as fish production, domestic use, and recycling as cooling water.

II WASTE HEAT FROM INDUSTRY

A General

There are few industries in the United States that do not to some extent add to the thermal loading on the nation's waterways. Almost one-half of all water used in this country is utilized for cooling and condensing by the power and manufacturing industries. The electric power industry accounts for more than eighty percent of the total cooling water used (Table 1). Although most industry uses water for cooling, not all heat entering the aquatic environment is from cooling water. In many instances process waters contain a thermal pollution load in addition to other contaminants.

B Electrical Power Production

Because the power industry accounts for such a large portion of total cooling water usage, power requirements offer a good correlation to future waste heat loads. Production of electricity has become a more efficient process throughout the years, that is the net heat rate (the number of BTU's needed to generate on KWH) has declined an average of 2.8% per year over the past 40 years. Even with this increase in efficiency, however, total power generation has increased at a net rate of 7.2% annually. That is, doubled every 10 years resulting in greatly expanded cooling water use. Comparatively, manufactured goods production is expected to increase by 4.5% annually over the next few years, and cooling water requirements will increase correspondingly. This rate indicates doubling every 16 years.

Because of a number of factors, heat rejection is expected to increase at least as fast as power production. First of all, fossil-fueled plants are approaching a limit of efficiency, that is, each incremental gain in efficiency is becoming harder to attain. Secondly, the advent of nuclear power will increase heat rejection because of nuclear plants' inherent lower efficiency than fossil-fueled plants. Finally, hydro power will constitute a smaller percentage of the new generating capacity in the future because remaining sites are rapidly being depleted. This is very evident in the Northwest, where the present hydro-base of power will gradually change to a thermal base.

Indications are that waste heat load from power plants, on a national basis, will double before 1980 and probably increase ninefold by the year 2000.

An understanding of the steam cycle may assist in evaluating the problem.

TABLE 1

USE OF COOLING WATER BY U.S. INDUSTRY, 1964

Industry	Cooling Water Intake (Billions of Gallons)	% of Total
Electric Power	40,680	81.3
Primary Metals	3,387	6.8
Chemical and Allied Products	3,120	6.2
Petroleum and Coal Products	1,212	2.4
Paper and Allied Products	607	1.2
Food and Kindred Products	392	0.8
Machinery	164	0.3
Rubber and Plastics	128	0.3
Transportation Equipment	102	0.2
All Other	273	0.5
TOTAL	50,065	100.0

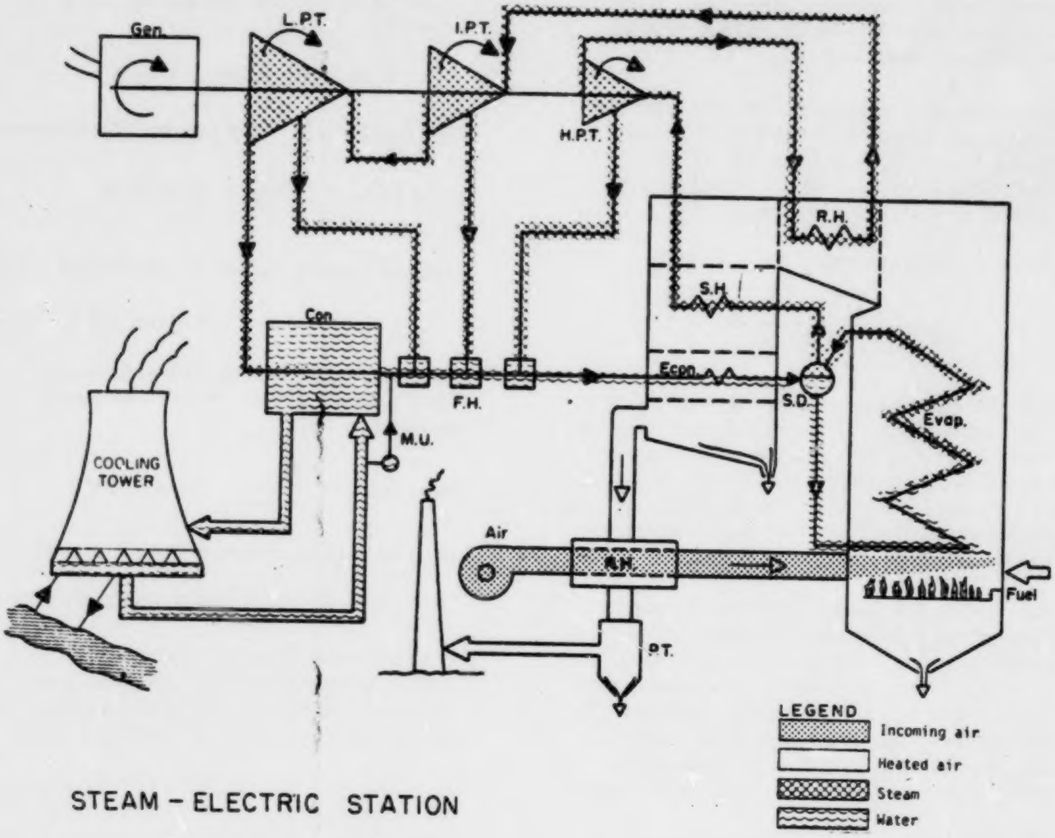
The basic steam plant cycle is as follows: the steam drum furnace combination turns water into high-pressure steam, which is carried to the turbines at a speed of about 200 miles per hour. Within 1/30th of a second the steam rushes through the turbines, traveling through a series of stationary nozzles and revolving buckets which spin the turbine rotor and connected generator shaft at either 1800 or 3600 revolutions per minute.

Drastic changes occur in the steam as it releases its energy to the rotating buckets. Steam may enter the turbines at temperatures of over 1000° F and leave at less than 100° F. It enters at a pressure of 2000 or more psi, expands to a thousand times its entrance volume, and leaves at a pressure less than atmospheric.

From the turbine exhaust the expanded, low-pressure steam goes to the condenser, where it is cooled until it condenses to water. The process reduces the volume of the steam by a factor of 27,000 in a near-perfect vacuum, thereby returning it to a state in which it can be easily handled. The water is returned to the boiler through the feedwater heater to be used over and over again as the cycle continues endlessly.

As the cycle repeats, it is necessary to continuously remove from the condenser an amount of heat equal to that given up in converting exhaust steam into water. Plant and operational refinements reduce the amount of heat entrained in exhaust steam which, in effect, increases the overall plant thermal efficiency.

Nuclear-fueled plants are inherently less efficient than fossil-fueled plants even though they too utilize the basic steam cycle to spin turbines and generate power. The major factor in the efficiency limitation is that imposed through reduced operating temperatures. Technological difficulties make it impractical, uneconomical, or unsafe to produce high-pressure, superheated steam in a water-cooled reactor system. Whereas modern fossil-fueled plants utilize steam at temperatures near 1050° F and pressures over 3000 psi, nuclear-fueled reactors of the boiling


Gen.
L.P.T.
I.P.T.
H.P.T.
R.H.
S.H.
Con
Econ.
S.D.
F.H.
M.U.
Evap.
COOLING TOWER
Air
A.H.
P.T.
Fuel
LEGEND
Incoming air
Heated air
Steam
Water

STEAM - ELECTRIC STATION

A.H.	Air Heater
Con.	Condenser
Econ.	Economizer
Evap.	Evaporator
F.H.	Feedwater Heater
Gen.	Generator
H.P.T.	High Pressure Turbine
I.P.T.	Intermediate Pressure Turbine
L.P.T.	Low Pressure Turbine
M.U.	Make-up (water)
P.T.	Electrostatic Precipitator
R.H.	Reheater
S.D.	Steam Drum
S.H.	Super Heater

water or pressurized water types produce steam at about 600° F and about 1000 psi or 2000 psi, respectively.

The efficiency of a power plant naturally affects the amount of waste heat rejected to cooling water. Efficiency, n_t, is the electrical output divided by the thermal input times 100, for percent.

For one kilowatt hour:

$$n_t = \frac{3413}{3413 + \text{Waste Heat}} \times 100$$

One kilowatt-hour is equal to 3413 BTU's. The denominator of the efficiency equation represents the heat required to produce one kilowatt-hour of electricity. It is used as a measure of a plant's efficiency, being inversely proportional to efficiency itself, and is called the plant "heat rate."

The national average heat rate at the present time is around 10,400 BTU's -- which means it takes 10,400 BTU's to generate 1 kwh of electricity equal to only 3,413 BTU's. The difference between the two figures, almost 7,000 BTU's is rejected to cooling water or lost to the atmosphere through plant and stack losses.

The heat rate of even the best present day fossil-fueled plants is about 8,500 BTU's. So we see that, even at best, we must somehow dissipate about 5,000 BTU's of heat for each kwh of electricity we produce.

We can evaluate more closely the amount of heat rejected to cooling water from a plant, knowing the efficiency or heat rate and by assuming some reasonable plant losses. For fossil-fueled plants losses account for about 15% of the thermal input, which is the heat rate. About 10% goes out the stack; 5% is lost within the plant. So the heat that must be rejected to cooling water, per kwh, is equal to:

$$\text{Ht. to CW} = 0.85 \times \text{Heat Rate} - 3413$$

For a nuclear plant, stack losses are not involved and the in-plant losses are taken to be 5% of the input. Therefore, the heat rejected to cooling water, per kwh, is equal to:

$$0.95 \times \text{Heat Rate} - 3413$$

For a fossil-fueled plant at 40% efficiency:

$$\text{Heat Rate} = \frac{3413}{.40} = 8533 \text{ BTU}$$

$$\text{Heat to cooling water} = 0.85\,(8533) - 3413$$

$$= \text{about } 3800 \text{ BTU/KWH}$$

for a nuclear plant at 33% efficiency: (that's about the maximum for plants planned to 1975)

$$\text{Heat Rate} = \frac{3413}{.33} = 10,340 \text{ BTU}$$

$$\text{Heat to cooling water} = 0.95\,(10,340) - 3413$$

$$= \text{about } 6400 \text{ BTU/KWH}$$

It can be seen that nuclear plants will not lessen the potential thermal pollution problem. Instead, they will reject about 65% more waste heat to cooling water.

For example, consider 1000 MW plants. As calculated for a 40% efficient fossil-fueled plant, waste heat to cooling water is about 3800 BTU/KWH. For a 1000 MW plant, the total heat output would then be 3.8×10^9 BTU/hr. Such a plant might circulate 1000 cfs through it. (= to stream 20 ft wide, 10 ft deep, running at 5 ft/sec). The temperature of this 1000 cfs would be raised 17° F through the 1000 MW fossil-fueled plant.

Heat from a 1000 MW nuclear-fueled plant would be 6.4×10^9 BTU/hr. If, for comparison, we want a 17° F temperature rise through this plant also, it would require a cooling water flow of 1650 cfs.

The following relationship can be used to determine a heat load (H_L) streamflow (S_f), or temperature (ΔT) rise if values are known for 2 of the 3 factors.

$$\Delta T = \frac{H_L}{S_f \times 62.4}$$

where: ΔT = change in stream water temperature, ^{o}F

H_L = heat load in BTU/sec and

S_f = streamflow in cubic feet per second

62.4 = Wt. of water, lb/cu.ft.

C Manufacturing Industries

As shown in Table 1, about 80% of all industrial cooling water is used by the power industry, and the remaining 20% by manufacturing industries. Manufacturer's cooling facility needs are expected to increase at a 4.5% annual rate, compared to the 7.2% annual increase expected by the power industry.

To assess the impact of an industry or an industrial complex on the thermal properties of a stream, one must determine the quantity of waste heat, i.e., total BTU's, discharged from each plant. Specific values of heat wasted by various processes are generally not applicable to individual plants, due to the wide range of production processes, equipment combinations, and efficiencies employed. Therefore, no attempt to formulate quantitative guidelines will be made here. Rather, it is suggested that the situation be approached through studying each manufacturing plant's discharge and sources of heat additions both to process waters and cooling water streams. In this manner, incorrect assumptions will not be used and a more valid heat load determination will be assured.

ACKNOWLEDGMENT:

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This outline was prepared by Lyman J. Nielson, Manpower Development Training Officer, OWP, EPA, Region X, Corvallis, OR 97330.

27

DATA REQUIREMENTS, FIELD STUDIES, AND INSTRUMENTATION FOR TEMPERATURE PREDICTION

I INTRODUCTION

Some simple basic equations which can be used to predict temperatures with certain simplifying assumptions have been developed. The following discussion concerns methods for acquiring the physical data necessary to the solution of these equations.

The first thing to be done in any situation is to learn if any data are already available and if it is suitable for the intended purpose. Two basic types of data are required--hydrologic and meterologic.

Two good sources for hydrologic information are the U.S. Geological Survey and the Corps of Engineers. Meteorologic information is available from the U.S. Weather Bureau and the Federal Aviation Agency. These four Federal agencies would be the first to contact although many other sources might be available.

II DATA REQUIREMENTS

In order to assess the data required, each situation must be examined independently.

A Example Problem

A 1000 megawatt electric output nuclear power plant is to be located on a well-mixed river. The problem is to determine the effect this plant will have on down-stream temperatures.

1 Assume there is not adequate Weather Bureau data available, and the information necessary to solve the basic stream temperature prediction equations developed earlier must be collected. Further assume major interest is in summer (June-September) temperatures, and the study must be completed in only one summer. Adequate hydrologic data is available, so only meteorological data will be obtained. Since only one summer's data can be collected, it will be necessary to rely on comparisons with past regional weather data to determine whether this one summer was average or whether it was hotter or colder than average. Extreme conditions will be estimated from the collected data and its relationship to past regional data.

2 Under the circumstances described, it would be necessary to do a fairly intensive survey of relevant meteorological conditions at the site, plus acquiring river temperatures at several points down-stream. Recorders should be used as much as possible in order to obtain continuous records of variations in the measured parameters.

3 What data should be obtained? This question may be answered by examining the basic equations.

a Energy exchange coefficient

$$K = 15.7 + (0.26 + B)\,bw$$

b Equilibrium temperature

$$E + \frac{0.051\,E^2}{K} = \frac{H_R - 1801}{K} + \frac{K - 15.7}{K}$$

$$\frac{e_a - C\,(\beta)}{0.26 + \beta} + \frac{0.26\,T_a}{0.26 + \beta}$$

c Stream temperature

$$T_x = (T_o - E)_e \;\alpha X + E = \frac{-K}{pC_{py}U}$$

4 The following physical variables are required to solve the preceding equations:

a Wind speed (w)

b Net radiation input (H_R)

c Vapor pressure of ambient air (e_a)

d Air temperature (T_a)

e Water temperature (T_o)

f Stream depth (y)

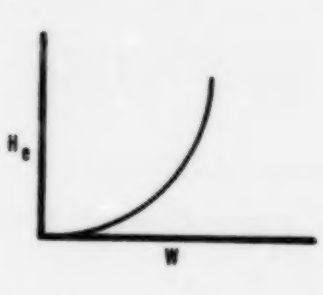
g Stream velocity (U)

III INSTRUMENTATION

Methods used to collect data will be considered. Comments will be restricted to the operation and design of the sensing elements of the instruments, and will not include methods of recording the information. Whenever an electrical signal or mechanical motion is an output, automatic recording can be achieved. The need for recording the data on a continuous basis depends on the type of study to be conducted, but should be practiced if at all possible.

A Wind Speed

Wind speed is one of the most critical meteorological variables in water temperature studies. As can be seen, wind speed is the only variable which affects K. It is sensitive to location, and care is necessary to assure an unobstructed air flow past the sensing device. In addition, the height above the ground or water surface at which the wind is measured is important.



A profile of wind speed near the ground is an exponential type curve (Figure 1) which, if plotted on semilog paper, would be linear. This type of profile exists within the turbulent boundary layer which may extend from 50 to several hundred feet above the surface of the earth. Thus, at any location, several different readings for wind speed could be obtained depending on the height at which it was measured. This fact is evident when one examines the various experimental equations for evaporation of the form:

$$H_e = bw\,(e_s - e_a) \text{ or } H_e = bW_z\,(e_s - e_a)$$

The z subscript indicates the height at which the wind and vapor pressure were measured.

Several types of anemometers are available. These include cup type, fan or blade type, pressure-tube, and hot-wire. The most common is the 3-cup type, which has a starting speed of less than two miles per hour, depending on the inertia of the cups. More sensitive units use light weight plastic cups to reduce inertia.

A fan type wind speed indicator such as a Biram anemometer is useful for making spot checks of wind speed.

B Net Radiation Input

Net radiation input is equal to incoming short-wave solar radiation plus atmospheric long-wave radiation minus reflected short-wave radiation minus reflected atmospheric radiation.

1 Solar radiation

Incoming solar short-wave radiation can be computed, but the calculations require several empirical coefficients. Therefore, it is usually measured.

a The instrument used to measure direct solar radiation at normal incidence is called a pyrheliometer. These instruments are mounted so as to always be directly facing the sun.

b Instruments which are used to measure solar radiation (including scattered) from the whole hemishere are called pyranometers. These instruments are placed so their detecting surfaces are level and they measure the solar radiation at all angles as the sun passes over. Since they are used to measure all 180° of the sun's radiation they are often called 180° pyrheliometers.

From a variety of available pyranometers, two of the most common are the Eppley type and Moll-Gorczynski type.

1) Eppley

- 2 concentric silver rings
- one white, one black
- temperature difference proportional to solar radiation intensity
- thermocouple junctions give voltage output
- a 50 junction model which is more sensitive than the 10 junction model

2) Kipp and Zonen solimeter

- flat black surface (to permit uniform absorption of long and short-wave) thermopile consisting of 14 thermo-couples
- both units give voltage output proportional to cal/cm^2 min.

c Care must be taken to place the pyranometer in a location where it will not be obstructed by shade. The glass which covers the units acts as a wavelength screen so that only short-wave radiation can reach the detecting surfaces.

C Atmospheric Long-Wave Radiation

This cannot be measured directly, except at night in the absence of solar radiation, and can be calculated only to within 10 to 20% of the actual value.

D Reflected Short-Wave Radiation

This could be measured by using a pyranometer point downward towards the water surface, but this is not usually done. It can be calculated from a knowledge of sun altitude, cloud height, and cloud cover. Sun altitude can be taken from a solar ephmeris and cloud height and cover are usually "eyeball" estimates. Empirical relationships are then used to compute short-wave reflectivity.

E Reflected Long-Wave Radiation

This cannot be measured directly, except at night, but it is estimated to be about 3% of the incoming long-wave radiation.

F Net Long-Wave and Short-Wave Radiation

Instruments are available which can measure the net radiation through a horizontal surface. These are pyrradiometers and the two most common types are the Gier and Dunkle flat plate radiometer and the Thornthwaite miniature net radiometer.

1 The Gier and Dunkle radiometer uses a thermopile (groups of thermocouples) in the form of a flat plate which is mounted on the end of a blower tube to maintain air flow over both sides of the plate. This prevents unequal convection currents from developing on either side of the plate. The thermopile indicates the temperature difference between the top and bottom of the plate which is proportional to the net radiation.

2 The Thornthwaite miniature net radiometer consists of a thermopile which measures the temperatures of both sides of a black disc. The disc is covered on top and bottom by hemispheres of clear polyethylene which is transparent to all relevant wavelengths and has a low absorption. The pressure inside the hemisphere is about 2 psi and the air is dried before being inserted into the space to prevent moisture from entering the area.

These meters measure both the net radiation input (H_R) and the back radiation (H_{br}). Therefore, H_R is computed by subtracting H_{br} from the net radiation.

3 Another device which is used to measure net radiation is a Cummings Radiation Integrator. This device is merely an isolated pan of water on which energy budget calculations are performed. There are no set sizes, although 4 foot diameters and 20 inch depths are common. They are placed so as to be exposed to the same radiation conditions as the water body, but are usually sheltered from the wind to minimize evaporative and conductive-convective heat exchange. Water removed by evaporation is replaced as often as possible to maintain a constant mass. Temperature measurements are made in the pan, and the change in water temperature over a period of time indicates the total energy change. Since evaporative loss is known, convective exchange can be reasonably estimated via the Bowen Ration. Back radiation can also be easily computed and thus the remaining energy change is due to radiation. U.S.G.S. experiences with these units at both Lake Hefner and Lake Mead have been favorable. (Measurements needed: wet and dry bulb air temperature, water temperature, barometric pressure, and precipitation temperature).

G Vapor Pressure of Ambient Air (e_a)

The pressure of the water vapor in the air (e_a) can be computed by multiplying the relative humidity by the pressure of saturated water vapor in the air at the same temperature:

$$e_a = (\text{r.h.})\ (e_{sat} @ T_a)$$

e_{sat} is a constant for any air temperature and can be found in published psychrometric tables and other standard references (i.e., Handbook of Chemistry and Physics).

1 The relative humidity can be computed from the air temperature and either the wet-bulb or dew-point temperature.

2 The wet-bulb temperature of the air is found by passing an air stream over a wetted temperature sensing element. The latent heat lost by evaporation will lower the temperature of the sensing element until a heat balance is obtained. This steady state temperature is the wet-bulb temperature.

a The sling psychrometer is the type most often used. Fan aspirated psychrometers are becoming more popular. The Assmann type employs mercury thermometers and a spring wound fan motor.

3 Dew-point determinations are made with two basic types of units. One type employs a shiny surface which at the dew-point will cloud up. Electronic units are available for this type which uses changes in the character of the light reflected from the surface to record dew-points. Another type of dew-point detector uses a chemical compound such as lithium chloride which changes its electrical resistance under different moisture conditions. When this material becomes saturated the resistance will be constant, and the dew-point is indicated.

Regardless of whether dew-point or wet-bulb readings are used, they should be taken at the same height above the water surface as the wind speed.

4 Relative humidity (or e_a) can be determined with a wet-bulb temperature (and associated dry-bulb temperature) or a dew-point temperature.

  a Tables are available which relate the difference in air temperature and wet-bulb temperature (called wet-bulb depression) to relative humidity as a function of air temperature. The barometric pressure of the atmosphere also has a slight effect, and this is taken care of in the tables. (The higher the barometric pressure at a given wet-bulb depression the lower the relative humidity).

  b e_a can be directly obtained from dew-point measurements. The dew-point is the temperature at which the water vapor in the air becomes saturated. Therefore merely by looking up the saturated water vapor pressure at the dew-point will provide e_a.

  c Instruments called hygrometers are available for directly measuring relative humidity. These instruments use sensing elements, such as hair or animal membranes, which expand and contract with changes in moisture content. High quality hygrometers are reasonably accurate at moderate temperatures and between relative humidities of 30 to 80%. At low temperatures and at relative humidities outside these limits, the accuracy of hygrometers falls off.

H Air Temperature

1 Dry-bulb air temperature measurements should be made at the same level as wind speed and wet-bulb or dew-point determinations. Care must be taken not to expose the sensing element to direct sunlight, and some air movement is also desirable.

2 There are a variety of ways to measure temperature, including:

  a Mercury or alcohol filled glass thermometer

  b Bi-metallic deflection type (like on a home furnace thermostat)

  c Gas or liquid filled systems with Bourdon tubes

  d Electrical types

  - Thermocouples--junction of 2 dissimilar metals which generates a voltage when there is a temperature difference.

  - Thermistors--semi-conductor materials whose electrical resistance varies with temperature.

  - Resistance Thermometers--metallic materials whose resistance varies with temperature.

I Water Temperature (T_o)

1 For complex hydraulic situations with spacial temperature variations, care must be taken to position water temperature sensors in such a manner as to adequately describe the temperature regime. In a well-mixed water body, there is, by definition, no spacial variation in temperature, so the location of the sensing element is less critical. One factor which should be recognized is that the water temperature dependent heat exchange components of the energy budget are related to the surface water temperature. It is usually difficult to determine the temperature of the very thin top layer; however, it is normally assumed that a foot below the surface is adequate.

For the example problem, II-A, the river temperature would be continuously monitored at one point above the proposed site, at the site, and at several points below the plant. The spacing of the measuring points would depend on the time interval for which predictions are required and on the speed of the river. Any influent streams or downstream discharges from the plant would also require monitoring. The downstream temperatures will be used to check temperature predictions made for natural conditions, and can also be used as checks in the future to note changes from the river's natural thermal regime.

2 Basically, the same type of instruments are used for water temperature measurements as for air temperature determinations. However, water temperatures need to be measured at some distance from the indicating mechanism; therefore a connecting cable or tubing is required.

a The Whitney Underwater Thermometer is a very precise and accurate instrument. This model has a range of 0-40° C in eight 5° C stages. The instrument is very rugged and is specifically designed for field application. Cables of up to 1000 ft. can be ordered. Cables are marked at regular intervals for easy reading. The unit is especially useful for lake surveys.

b In the Foxboro liquid filled thermograph, the liquid changes its volume as the water temperature changes and a Bourdon tube actuates the pen. The unit is temperature compensated so the temperature inside the case will not affect the readings. The chart is driven by a spring wound motor. This unit has a temperature range of 30-90° F.

c These are only two of the many different types of equipment which can be used to measure water temperature. Most water temperature measurements are made by immersing the sensing element. However, remote sensing equipment is also available. Since water emits back body radiation at a rate proportional to the fourth power of the surface temperature, this back radiation can be used to determine surface temperatures. The past few years has seen the development of remote radiometers which are used to perform this function. Operated from airplanes, or even orbiting satellites, these devices can give an aerial picture of a water body's surface temperature. Such remote scanners are especially valuable for synoptic surveys over large distances.

J Stream Depth and Velocity

Hydrologic data and maps can be used to acquire this data. Stream velocity can be simply computed by $V = Q/A$.

K Remote Sensing of Thermal Pollution

Most outstanding of the work already done on the use of remote sensing techniques to determine the discharge and spread of heated waters has been the use of the NIMBUS satellite high resolution infrared imagery to detect contours of the Great Lakes (National Council on Marine Resources, 1967). Though some of the needed information in this area is still classified, sufficient data is known to enable one to use the technique and its airplane and laboratory versions to study the patterns of temperature distribution on water surfaces.

1 A number of commercial firms are available on a contract basis to provide complete service. Infrared wavelengths, in the 1.5 to 14 micron range are used in hydrologic studies because in this region the infrared energy emitted by land and water bodies is at a maximum and atmospheric absorption is at a minimum (Lukens, 1968). A typical scanner is sensitive to 1/4° C surface temperature changes and can be calibrated with surface instrumentation to 1/2° C.

2 A brief evaluation of the use of remote sensors in hydrology was presented at the International Conference on Water for Peace (Robinove, 1967). At that time, photographic sensors were still most favored because of the easy interpretability and the minimum data reduction and specialized training needed for their use. Infrared sensors offer hope of great things in thermal pollution work, but are hampered in a quantitative - not qualitative - sense at present by problems of emissivity measurement. In any case, infrared imagery is only a function of the surface temperature of the waters and does not give any indication of the thermal profile.

III CONCLUSION

The type of study will normally dictate the accuracy required of the data and this in turn will dictate the quality of the instruments required. It would be costly to buy extremely accurate instruments designed for sophisticated scientific studies if they were to be used only on preliminary surveys. On the other hand, trying to skimp on instruments can leave one with poor quality data which may be useless for its intended purpose. No hard and fast rules can be applied to equipment selection, but an evaluation of the potential uses of the instrument is necessary before a choice is made. Finally, a recorder should be as good as the instrument with which it will be used. A poor recorder will give questionable data no matter how good the measuring instrument.

With respect to cost, a complete meteorological setup of reasonably high quality would run about $4,000. A water temperature recorder would add to this figure.

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This outline was prepared by James A. Montgomery, Sanitary Engineer, River Basin Planning, OWP, EPA, Washington, DC 20242.

SUMMARY OUTLINE OF CURRENT THEORIES RELATING TO TEMPERATURE PREDICTION IN A BODY OF WATER

I INTRODUCTION

A The causes, effects, and methods of controlling thermal pollution have been discussed. The following analytical tools may be used to determine the physical impact of a potential thermal pollution source.

B The ability of the engineer working for regulatory agencies to accurately predict water temperatures is necessary in order to determine the thermal impact of:

1 Proposed waste heat discharges

2 Changes in the hydraulic characteristics of a water body or stream -- for example, due to dam construction

3 Releases of water from stratified reservoirs with multi-level outlets

4 Unusual meteorological conditions

In short, there is a need to be able to predict water temperature effects of any natural or man-caused phenomenon which may alter the hydrologic or meteorologic regime.

II THE ENERGY-BUDGET APPROACH

A The energy budget attempts to equate the net exchange of heat between a body of water and its environment to changes in water temperature. Energy-exchange processes normally considered include (Notations from Schroepfer):

1 The difference between incident and reflected solar radiation $(+\Delta T_s)$

2 The difference between incident and reflected atmospheric radiation and the loss of heat by thermal radiation from the water surface (i.e., net exchange of long-wave radiation) $(-\Delta T_R)$

3 The loss of heat due to evaporative processes $(-\Delta T_E)$

4 The gain or loss of heat due to temperature difference at the air-water interface $\pm (\Delta T_c)$

5 The heat gain due to discharge, for example, of cooling water into the reach $(+\Delta T_A)$

B These incremental temperatures, then, are added algebraically to the upstream temperature, T_A, to estimate the downstream interface temperature, T_B, as follows:

$$T_A + \Delta T_A + \Delta T_S - \Delta T_E \pm \Delta T_c - \Delta T_R = T_B$$

Other processes actually involved, but usually disregarded, are biochemical reactions and conduction of heat at the water-channel bottom interface.

Since computation of evaporation and thermal radiation exchange depend on the assumed downstream temperature, the equation cannot be solved directly. Formulae, such as the above, can be solved by successive trials assuming downstream temperatures, T_B.

C This method is used, equally well on streams in their natural, steady-state condition as on streams receiving large amounts of cooling water or cold, reservoir water.

For detailed descriptions of theory and data relative to individual energy-budget parameters, the interested reader is referred to several references in the bibliography (1, 6, 7, 8, 17).

III EQUILIBRIUM TEMPERATURES AND EXPONENTIAL DECAY OF TEMPERATURE INCREMENTS

This second approach is a two-fold operation.

A First, the steady-state, or equilibrium, temperature of the water is estimated by any one of several methods.

1 Energy-budget equations, as just discussed

2 Simple correlation with air temperature as Gameson, Hall and Preddy did on the Thames Estuary in 1957

e.g., The Thames Estuary data yielded the following relationship:

Equilibrium Temperature =

$$\theta = 0.5 + 1.109\ T_a$$

3 Estimation of the natural stream temperature according to its response to its thermal environment as expressed by Duttweiler's equations: Heat input =

$$T_{\varepsilon}(t) = \frac{Q_n - 25}{\lambda} + \frac{B_1 T_{ad} + C_B T_a}{B_1 + C_B}\,\frac{(\lambda - \frac{1}{2})}{\lambda}$$

$T_{\varepsilon}(t)$ = input temperature

$Q_n - 25$ = net radiation input

B_1 = slope of saturation vapor pressure vs. air temperature curve

T_{ad} = dewpoint temperature

C_B = bowen ratio coefficient (0.61)

T_a = air temperature

λ = heat exchange coefficient

Water temperature =

$$T(x,t) = T_m + \sum_{n=1}^{\alpha} T_{un} \sin(n\omega t + \phi_n - \alpha n)$$

$T(x,t)$ = water temperature with distance and time

T_m = mean temperature with time

∞ = infinity

u = absolute maximum and minimum value of water temperature

n = number of cycles

ω = $\pi/12$

t = time in hours

ϕ = arctan A_n/B_n where A and B are coordinates of the Amplitude Point

α = lag factor-arctan n /k

k = rate constant

The first of these equations is plotted from a knowledge of climatological data. Short time intervals will yield points on a modified sine curve.

The second equation is merely a reflection of the first modified by an amplification factor (T_u/T_1) and phase lag (α).

B Second, transient temperatures due to thermal additions are decayed exponentially downstream.

Regardless of what form the equilibrium temperature takes, transients can be accounted for by computing the initial temperature increment and reducing it exponentially downstream. The exponential decay factor can be expressed as follows:

$$e^{-\frac{k}{v^{x}}}$$

Thus: $\Delta T_1 = \Delta T_o e^{-\frac{k}{v^x}}$

Where: v = average velocity

x = dist. downstream

And: k has been evaluated by Major Duttweiler as $\frac{\lambda}{z}$

Where: z = average depth

And: $\lambda = C_1 + C_2U_2 = 1.35 + 0.2\,U_2$

Where: U_2 = estimated wind speed in mph

ACKNOWLEDGMENT:

Materials for this outline were taken from "Summary of Current Theories and Studies Relating to Temperature Prediction." 12th Pacific Northwest Symposium on Water Pollution Research. Water Temperature, Influence, Effects and Control manual. Presentation by Robert Zeller.

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THERMAL POLLUTION CONTROL METHODS

I INTRODUCTION

Nationally, thermal pollution has become an increasingly important topic for consideration in water management and pollution control circles. With the approval of State-Federal water quality standards, the criteria and implementation plans for control of waste heat discharges have been established. This outline will consider several of the accepted methods now being used to control thermal pollution.

II CONTROL IN INDUSTRY

A Industrial process changes to reduce waste heat production.

Efficiency gains in fossil-fueled, steam-electric stations have reduced their waste heat discharge rate by approximately one-half over the past 30 years. Such gains have been accomplished through a number of refinements in the plant itself and in operating conditions, which increases the overall plant thermal efficiency by reducing the amount of heat entrained in the exhaust steam. The refinements that have been developed include the following:

1 Increasing steam pressure--elevating the steam pressure at the turbine entrance reduces exhaust heat by varying increments, but in general a 100 psi pressure increase will reduce exhaust heat per unit of electricity by 0.4%.

2 Superheating steam--steam generated in the boiler is heated even more in a superheat section of the furnace. Each 50°F additional temperature rise reduces exhaust heat per unit of electricity by about 1.4%.

3 Reheating steam--after the steam has passed through the high-pressure turbine section it is returned to the furnace reheat section to absorb additional heat energy. Again, each 50°F increase here reduces exhaust heat per unit of electricity by about 1.4%.

4 Boiler feedwater heating--a portion of the steam is withdrawn before it reaches the final turbine exhaust, thereby eliminating its passage through the condenser. This steam is utilized to increase the temperature of water entering the boiler. Feedwater heating can reduce exhaust heat up to 37% per unit of electricity, depending on the number of heaters used.

5 Reducing exhaust pressure--the pressure in the condenser is transmitted to the turbine exhaust, i.e., turbine backpressure. This pressure influences heat rejection to the extent that each 1 psi reduction in pressure reduces exhaust heat per unit of electricity by 2.5%.

Modern power plants are designed to make use of these efficiency refinements as much as possible. Through such techniques, new fossil-fueled plants attain efficiencies near 40%; nuclear-fueled plants about 33%.

B Development of new methods of power generation producing less waste heat production.

Generating processes are more efficient today than they were 25 to 30 years ago, but they are still not good enough. Today, we use about 10,000 BTU's to produce one kwhr, on the average, compared with 16,500 BTU's per kwhr in 1938. Some highly efficient new plants are down to 8,900 BTU's per kwhr, but this is still only 38.2% efficiency. The Federal Power Commission suggests that average heat rates of 8,500 BTU's per kwhr are likely by 1980. While this would reduce thermal pollution by almost 20%, it still means only 40.2% efficiency. At best, then, by 1980, 60% of the heat from a coal-fired plant will be wasted and will have to be put to other uses or dissipated.

New and non-polluting methods of power generation are being intensively researched. High temperature gas turbine-blade cooling could result in a 50% reduction of the cooling waters required. Electrogasdynamics, magnetohydrodynamics, and thermionic power generation, if they can be developed economically, could greatly reduce our water- and air-pollution problems. Fuel cells and thermal electrical systems which do not require steam cycles for power generation also are being studied and present hope for the future.

1 Gas turbines--air is taken from the atmosphere, compressed, and subsequently burned with a liquid or gaseous fuel. The resulting high-temperature, high-pressure gases expand through a power turbine and then exit to the atmosphere.

Today's gas turbine efficiencies of less than 25% are not competitive for power production on a large scale, although some relatively small turbines are being used for standby and peaking operation. Future development may achieve higher operating temperatures and increased air flow, which in turn would increase efficiency to a level near that of fossil-fueled steam plants.

Heat exhausted from gas turbines might possibly be put to use in a conventional steam-electric plant. Such a combination would reduce the waste heat discharge rate, although cooling water would still be used.

2 Fuel cells--fuel cells are somewhat similar to conventional storage batteries in that they consist of two electrodes separated by an electrolyte. The fuel cell does not contain a store of energy; it generates current as long as fuel and oxidant supply chemical energy for conversion to electricity.

Individual fuel cells produce very small quantities of power. Hence, thousands of cells would have to be connected in groups to increase power output to a level which would permit large-scale production. Predicted eventual efficiencies of 50 to 85% is a further attribute of the fuel cell system.

3 Magnetohydrodynamics (MHD) generators--MHD generators utilize the principle of passing a conductor through a magnetic field to produce current. In this system the moving conductor is an ionized gas. Very high temperatures and gas velocities must be maintained, which at the present time presents some major technical difficulties. In theory, the application of a MHD generator can be visualized, possibly in combined operation with a conventional steam plant, but major advances in materials must be achieved before the future of MHD Power generation can be predicted.

4 Nuclear fueled steam electric plants--The principal advantage of nuclear fuel is its tremendous energy density. One ton of uranium has the energy potential of three million tons of coals. Present-day reactors convert only about 0.5% of this energy to usable heat, i.e., combustion efficiency is 0.5%. Advanced reactor design, i.e., breeder types, will convert much more energy into a useful form. However, while advanced designs will improve fuel consumption, they will not necessarily increase the thermal efficiency to reduce waste heat in steam-electric plant operation.

Reduction of waste heat output from nuclear plants will depend on development of advanced converters which will allow higher operating temperatures. Such converters will employ a reactor coolant other than water in the primary flow loop, which circulates fluid through the reactor core for heat absorbtion. The heat is then transferred to steam through a heat exchange process in a steam generator. Systems of this type, still in developmental stages, are using fluids such as helium, liquid sodium or liquid potassium for coolants. Reactor outlet temperatures of over 1000° F are possible.

Because of the vast energy stores in nuclear fuel, its utilization for power production is inevitable. For the next 15 to 20 years, the number of plants in the 30% efficiency class will increase rapidly, which indicates that more efficient systems will surely lag behind our demands for power. This being the case, our immediate efforts must focus on waste heat utilization and dissipation while technology is being developed for more efficient power production methods.

C Waste Heat Energy Utilization

The optimum solution to problems associated with waste heat disposal would be the use of rejected heat for beneficial purposes. When dealing with power plant discharges, however, one is confronted with immense quantities of water which are of low quality when considered as a heat source. Utilization of waste heat in this form is therefore restricted to only a very few possible applications.

1 Agriculture--one potential for such utilization is the farming of plants or animals in fresh or salt water. This has already been successfully practiced in Japan and elsewhere. Heated discharges are used to enhance the environment and increase production of commercially valuable species such as pompano, catfish, shrimp, oysters, and scallops. Research, development, and pilot studies are in progress to determine the feasibility of such cultivation in American waters.

Heated discharges may have application in irrigating and creating controlled environments for agricultural crops. In this manner, growing seasons could be lengthened in certain areas for common crops, and subtropical or tropical varieties might be produced where they are not normally adaptable.

2 Commercial shipping--some nuclear plants could possibly be located to provide beneficial use of heated discharges in keeping shipping lanes free from ice for extended seasons. The recommendation for such application to the St. Lawrence Seaway has been proposed to extend the shipping season to the end of December or even January.

3 Recreation--cooling water may provide heat to warm swimming areas. Such use should be guided by the National Technical Advisory Committee on Water Quality Criteria which recommends: "In primary contact recreation waters, except where caused by natural conditions, maximum water temperature should not exceed 30°C (85°F).

4 Industrial utilization--perhaps the most logical use for the waste heat is to plan for its conversion into an inexpensive energy source for satellite industries that will be constructed simultaneously with the power plant.

When there is no longer any question that the waste heat cannot be put into the nearest body of water, then our American industrial ingenuity will certainly solve the problem of turning this waste heat into an economic asset that can be sold, rather than spend millions of dollars for cooling towers just to get rid of it.

Our industries are based on the use of energy; vast sums of money are spent for it. Why not surround the power plant with new industry and bring about the development of nuclear--industrial parks? Why not computerize the planning of entire industrial complexes based on a nuclear power center instead of our present disorganized approach to industrial siting? We may stand on the brink of a modern industrial revolution which could be triggered by the absurd fact that fish can't stand heat.

D Alternative methods to thermal discharge or waste heat utilization.

There are several methods providing air-water contact for removal of waste heat from water through evaporation and/or conduction-convection. As water is vaporized, heat is consumed at the rate of approximately 1000 BTU per pound of water evaporated. About 75% of heat loss from cooling is accomplished through evaporation. The remainder is accomplished through conduction-convection losses.

The different types of cooling devices now being utilized include the following:

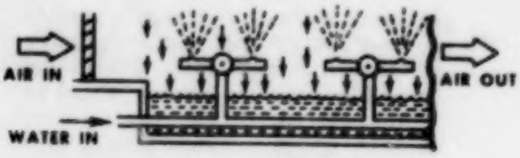
1 Cooling ponds--the cooling pond is the simplest and most economical method of water-cooling (assuming land is inexpensive and available); however, it is also the most inefficient. It may be constructed simply by erecting an earth dike 6 to 8 feet high and may operate for extended periods with no makeup water.

Its main disadvantages are the low heat-transfer rate and the large areas required. For a still pond, the heat dissipated averages 3.5 $BTU/hr/ft^2$ surface/degree temperature difference between pond surface and air.

2 Spray ponds--cooling can be accelerated in a pond by introducing the warm water through a spray system located 6 to 8 feet above the water surface. Such a system may reduce the required pond surface area by a factor of 20 through increased cooling efficiency. This advantageous savings in land area may be negated through spray system cost, pumping costs, and increased water loss with its associated problems.

Spray ponds may handle as much as 120,000 gpm of water and their low head requirements result in lower pumping costs than for cooling towers.

Performance is limited, however, by the relatively short contact time of air and water spray. Also, impurities may easily enter the system. Properly designed spray ponds may produce overall cooling efficiencies up to 60%. (Figure 1)



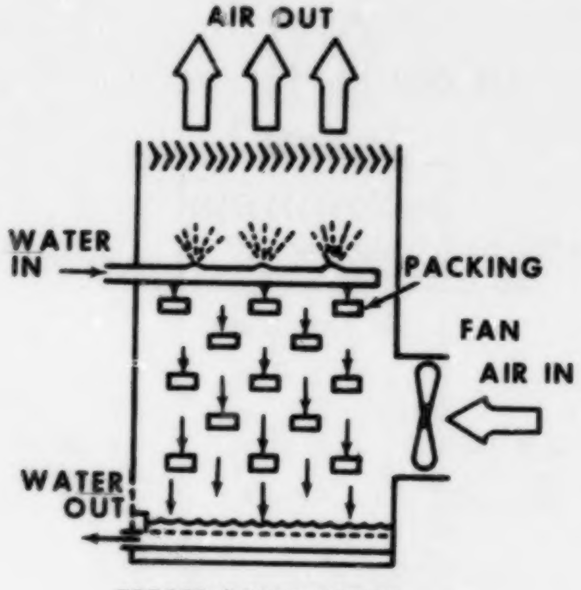
SPRAY POND

FIGURE 1

3 Cooling towers--the terminology applied to the many versions of cooling towers stems from basic differences in design or operation which serve to categorize the types.

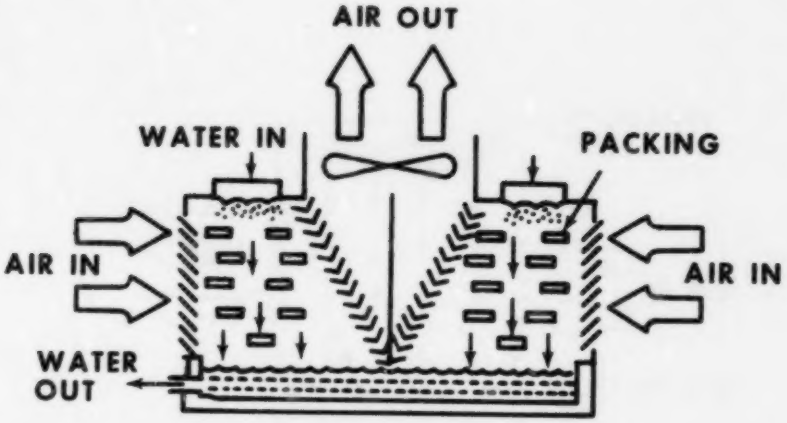
A tower may be either "wet or "dry," depending on whether water is exposed directly to the air; "natural draft" or "mechanical draft," depending on whether fans are employed for air movement; "cross-flow" or "counter-flow," depending on horizontal or vertical air flow through the heat transfer section of the tower. In mechanical draft towers, air flow can be either "forced," i.e., pushed through by fan on bottom, or "induced," i.e., pulled through by fan on top. See Figures 2, 3, 4, 5, 6, 7, and 8 illustrating these different types of cooling towers.

a Mechanical draft towers --as implied, the mechanical draft tower utilizes fans to move the air through the tower. Thus no dependence is placed on natural draft, or wind velocity. The arrangement of the fans dictates the method in which the air is moved through the system, each arrangement having certain advantages and disadvantages.


AIR OUT
WATER IN
PACKING
FAN
AIR IN
WATER OUT

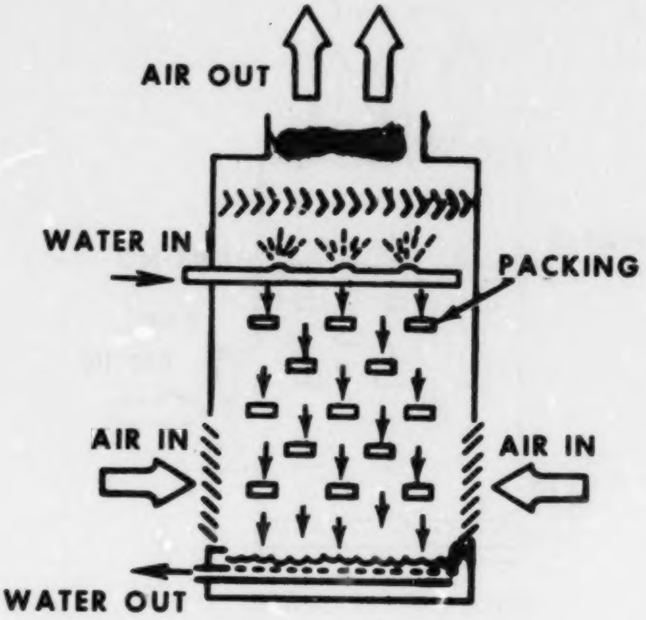
FORCED DRAFT TOWER

FIGURE 2


AIR OUT
WATER IN
PACKING
AIR IN
AIR IN
WATER OUT

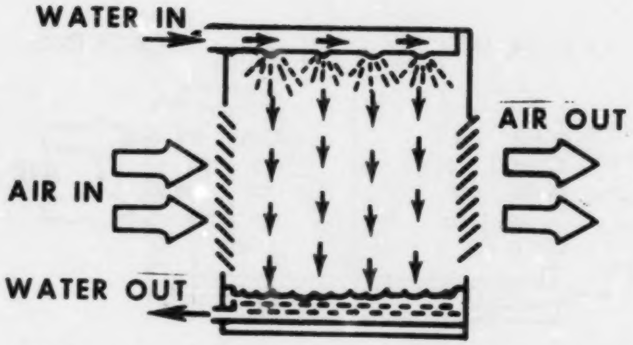
INDUCED DRAFT CROSSFLOW TOWER

FIGURE 3


AIR OUT
WATER IN
PACKING
AIR IN
AIR IN
WATER OUT

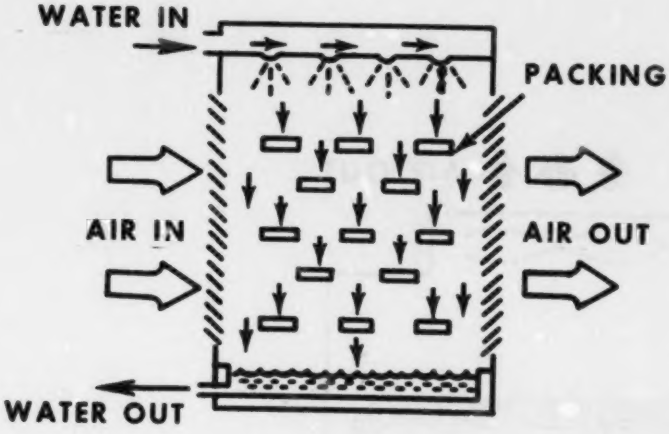
INDUCED DRAFT COUNTERFLOW TOWER

FIGURE 4


WATER IN
AIR OUT
AIR IN
WATER OUT

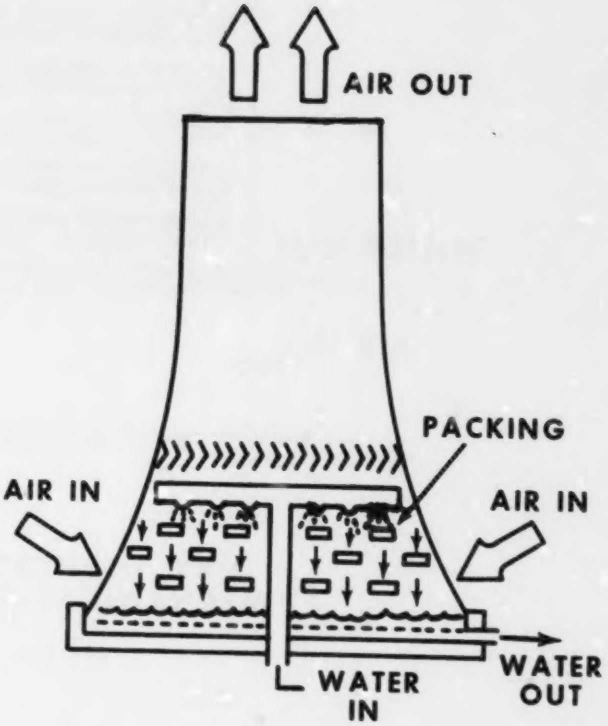
SPRAY-FILLED NATURAL DRAFT CROSSFLOW TOWER

FIGURE 5


WATER IN
PACKING
AIR IN
AIR OUT
WATER OUT

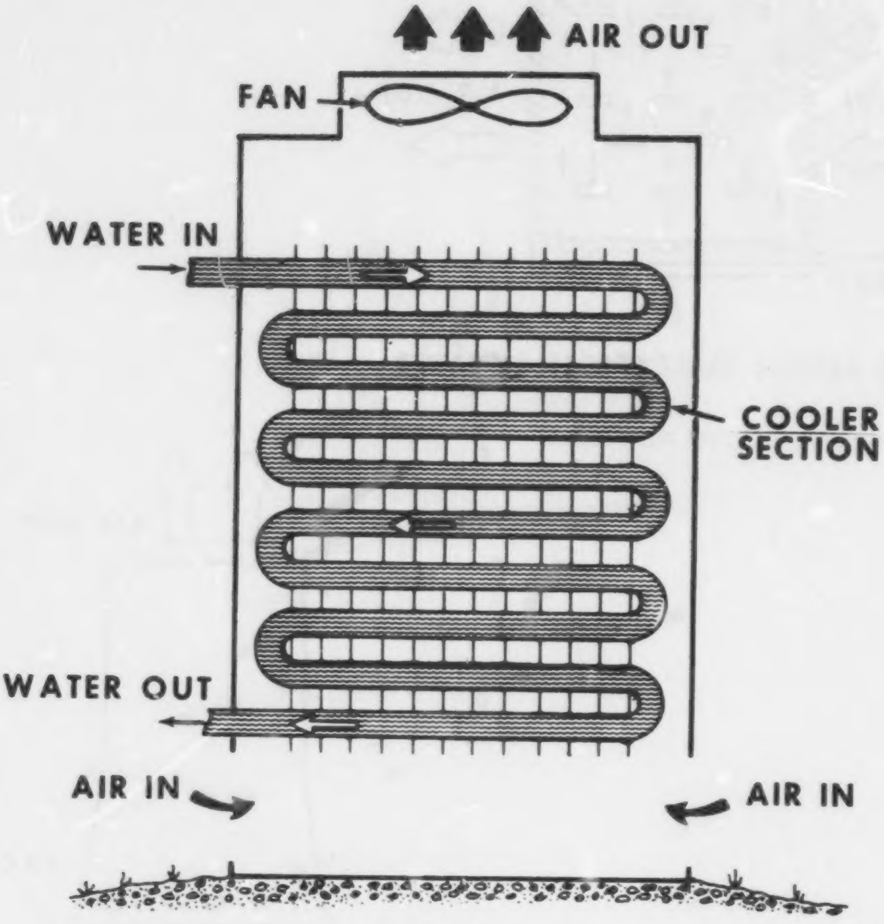
PACKED NATURAL DRAFT CROSSFLOW TOWER

FIGURE 6


AIR OUT
PACKING
AIR IN
AIR IN
WATER IN
WATER OUT

HYPERBOLIC TOWER

FIGURE 7


AIR OUT
FAN
WATER IN
COOLER SECTION
WATER OUT
AIR IN
AIR IN

DRY, INDUCED AIR FLOW MECHANICAL-DRAFT TOWER

FIGURE 8

b Natural draft or atmospheric towers--an atmospheric tower implies that air movement through the tower is only dependent on atmospheric conditions. A spray-filled tower depends solely on spray nozzles for increasing the air-water interface, while the packed tower sprays the water over filling or packing. The packed tower is no longer common, however.

Atmospheric spray towers are of the simplest design and may cool up to 1.5 gpm of water per square foot of active horizontal area with the wind blowing at 5 MPH (Marks, 1963). Their advantages include no mechanical parts, low maintenance costs, no subjectivity to recirculation of used air, and long, trouble-free life.

Disadvantages include high initial cost (approximately identical to a mechanical-draft tower), high pumping head, location in an unobstructed area, required great length because of rather narrow construction, high wind losses, and nozzle clogging. This design is well suited for small operations, however.

c The chimney or hyperbolic towers--the hyperbolic tower operates similar to a huge chimney: the heavier outside air enters at the tower base, displaces the lighter, saturated air in the tower, and forces it out the top. The initial cost is higher, but it is balanced against savings in power, longer life, and less maintenance. Their operation is countercurrent, they can cope with large water loads, and they require a relatively small area.

These towers will probably become common in the United States as the cooling-tower requirements expand.

d The dry-cooling tower--the dry-cooling tower is not an evaporative cooling device; instead, it cools fluids by forcing or inducing atmospheric air across a coiled cross-section. They eliminate water problems, such as availability, chemical treatment, water pollution, and spray nuisance; and there is no upper limit to which air can be heated.

However, the dry-cooling tower is much less economical than an evaporative cooling device, the specific heat of air is only one fourth that of water, and maintenance costs are high.

Thus, the cost of dry-cooling towers is presently thought to be prohibitive for most installations, even though many conservationists believe these are the only answer to the thermal-pollution problem.

III FIELD CONTROL METHODS

A Logging Operations--measurements of summer temperatures in small streams flowing through logged and unlogged forest areas show water temperature increases of 14-16° F in the unprotected stream. Temperature increases of this magnitude produce stream temperatures which are far in excess of optimum and are even in the range of temperatures known to be damaging to resident and anadromous fish which spawn, grow, and migrate in the small forest streams. Such increased temperatures make possible the rapid growth of trash fish, slime bacteria, and algae.

Soil erosion on, and logging debris from, roads, landings, skidways, and slopes disturbed by yarding activities during a logging operation can also seriously affect streams. Much of this damage can be prevented by using all reasonable means and alternatives that will keep every road and logging activity as far from the stream courses as possible.

B Agriculture--clearing of fields to the water's edge exposes the stream to the full impact of heating by the sun with resulting increases in water temperatures.

Therefore, leave buffer strips of native vegetation, including an overhead canopy, between cleared fields and any perennial streams they parallel. Buffer strips not only reduce the quantity of sediment and pesticide and fertilizer drainage that reach the streams, but also help prevent stream water temperature increases and loss of natural stream beauty. Thus, they assist with the preservation of water quality and the attainment of temperature objectives for fish management.

IV SUMMARY

We see that there are methods available for reducing or controlling thermal pollution through process changes and the development of new methods of power generation. The advances that have been made, however, have been slow in coming. Waste heat utilization, therefore, takes on more and more importance as it is obvious that water quality standards set for interstate streams and coastal waters can only be expected to become more stringent in the future.

ACKNOWLEDGMENT:

Material for this outline taken from the following sources: "Thermal Pollution, 1968, Part I, Hearings before the Subcommittee on Air and Water Pollution;" "Thermal Pollution: Status of the Art," by Frank L. Parker and Peter A. Krenkel; "Industrial Waste Guide Logging Practices," February 1970, FWQA; "Biological Aspects of Thermal Pollution," Vanderbilt University Press, 1968, by Frank L. Parker and Peter A. Krenkel; "Engineering Aspects of Thermal Pollution," Vanderbilt University Press, 1969, by Frank L. Parker and Peter A. Krenkel; and "Industrial Waste Guide on Thermal Pollution," September 1968 (revised), FWQA.

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SECTION III SOLIDS LIQUID SEPARATION

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Solids Removal Processes	10
Sedimentation Basins in Wastewater Treatment	11
Sedimentation Tank Equipment	12
Settling Tank Operation	13
Dissolved Air Flotation	14
Sludge Dewatering	15
Centrifugation	16
Liquid to Solids Transfer	17

SOLIDS REMOVAL PROCESSES

I INTRODUCTION

If one were to rank wastewater treatment operations in order of overall importance, separation of solids from liquids would probably assume major importance. This operation may be required to remove objectionable components from a waste, to render the waste more amenable to subsequent treatment or disposal, or to support another treatment operation.

II SEDIMENTATION

Sedimentation tanks are employed for various applications which have one common objective - the removal of solid matter from a flowing liquid. The solid matter may have been present in direct suspension, such as in municipal sewage, or may alternatively be a precipitate resulting from prior chemical treatment, such as lime precipitation, alum, or iron coagulation.

A Horizontal Flow Design

1 The principal basis of the earliest designs of horizontal-flow sedimentation tank was the "retention time". The objective was to move water so slowly through the tank that there would be ample time for settlement. The nominal detention period allowed was usually more than four hours.

a However, each drop of water did not take the same time to travel from inlet to outlet, since some degree of "short-circuiting" was bound to occur.

b A typical pattern of flow under ideal conditions in an elementary design of a horizontal-flow tank is represented by Fig. 1. Diagram (a), solid line, represents the most favored flow-path, while the dotted lines indicate typical eddies which are induced in the remainder of the tank volume. Diagrams (b) and (c) represent the flows which result, respectively, to entering water being warmer or colder than the water in the tank.

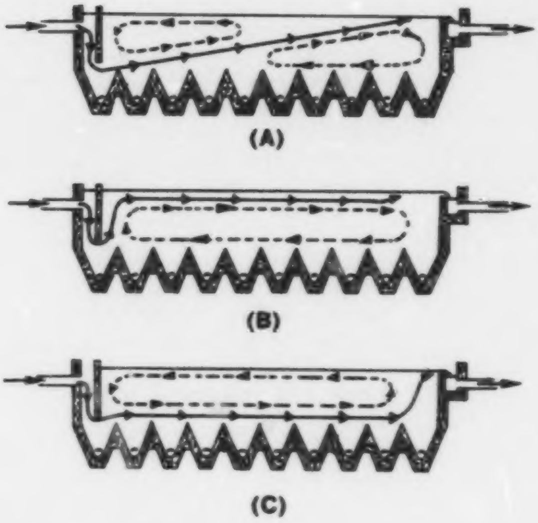


FIGURE 1 SEDIMENTATION TANK OF HORIZONTAL - FLOW TYPE UNDER DIFFERENT CONDITIONS OF RELATIVE TEMPERATURE

2 The basic design which has been most widely used for sewage treatment is a tank circular in plan. The inflow is introduced at the center of the tank and the outflow is collected at a peripheral launder. As the general direction of flow is mainly a radial spread from the center, it is reasonable to regard this design as in the horizontal-flow category as in Fig. 1.

3 Vertical-Upflow Design

a The improved performance obtained in upflow tanks has led to a variety of new designs, incorporating variants of the upflow principle. These new designs are designated by various proprietary names - Accelator, Clarifow, Flocsettler, Reactor-Clarifier, etc. One of the earliest of the upflow tanks was the Spaulding Precipitator, shown in Fig. 2. In this design, the flow is introduced into the center of the tank and flows upward through a blanket of previously formed solids.

b The principal advantages of the upflow versus the horizontal tanks are (1) improved flow control, and (2) sludge blanket effect. Salt-injection tests performed on a variety of tank designs clearly show the superior efficiency of the upflow principle in the matter of flow control. The radial-flow still largely used in sewage treatment is distinctly inferior, being subject to short-circuiting.

4 Tube and Lamella Settlers

In an ideal settling basin, as defined by Camp, the paths of all discrete particles will be straight lines, and all particles with the same settling velocity will move in parallel paths.

a The settling pattern shown in Fig. 3 would be the same for all longitudinal sections. It is apparent from this that as the interval (h) is reduced, the size of the basin required to remove a given percentage of the incoming settleable material decreases.

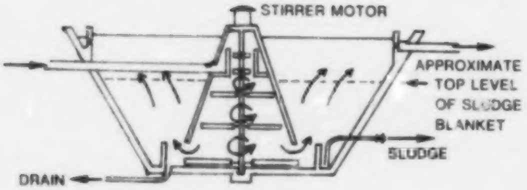


FIGURE 2 SPAULDING PRECIPITATOR

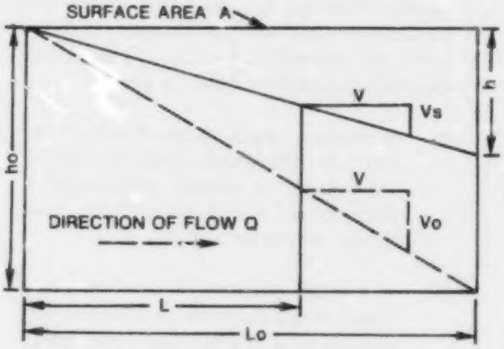


FIGURE 3 IDEALIZED SETTLING PATHS OF DISCRETE PARTICLES IN A HORIZONTAL FLOW TANK

b Many devices have been proposed since this principle was first proposed by Hazen in 1904 and further developed by Camp in 1946.

c None of the proposed devices were accepted commercially until the recent introduction of the device called the tube settler. These consist essentially of closely packed small diameter tubes, 1-4 inches in diameter and 2-4 feet in length, inclined at some angle to provide for removal of sludge as the water flows upward through the tubes. Detention times are in the order of 6 minutes and less. The tubes provide as much as 24 hours of sludge storage, depending of course, on the amount of suspended solids, and sludge is readily removed by gravity drainage.

1 A schematic diagram of the tube settler integrated into a complete clarification device which consists of coagulation-flocculation, a tube settler unit and a mixed media filter is shown in Fig. 4.

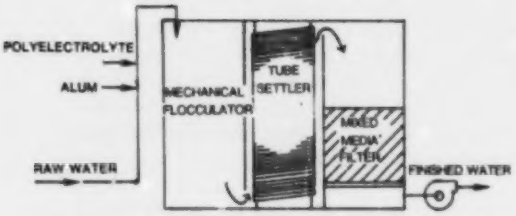
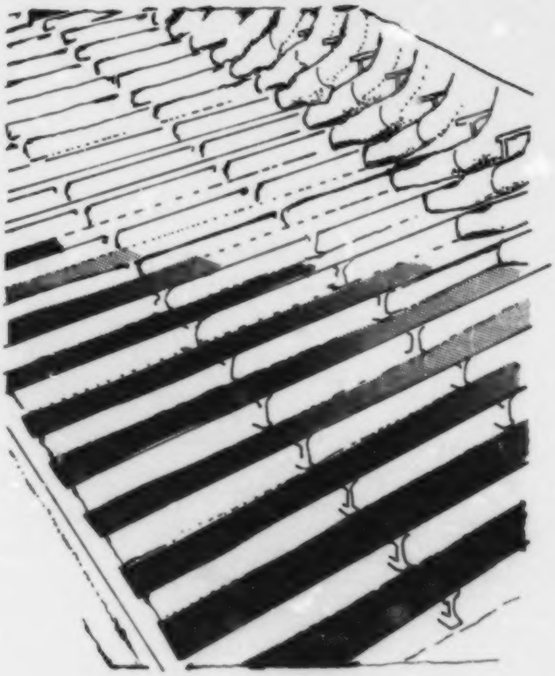


FIGURE 4 SCHEMATIC DIAGRAM OF APPARATUS USED IN FIELD TESTS OF TUBE SETTLER

2 More recently, a device consisting of parallel plates rather than tubes has become available. The device is called a lamella. Flow is co-current in contrast to the countercurrent flow of the tube settlers. The plate arrangement in a tank is shown in Fig. 5.

FIGURE 5 LAMELLA SEPARATOR

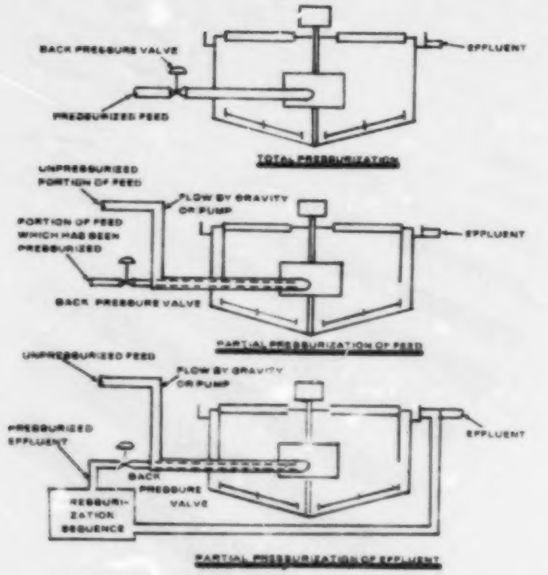


III DISSOLVED AIR FLOTATION

A The use of dissolved air to float suspended solids was first used in industrial operations. In recent years, the process has been adapted to domestic wastewater and particularly, to sludge thickening. The process achieves the separation of suspended particles by attachment of gas bubbles to the suspended particles, thereby reducing the effective specific gravity of the particles to less than that of the water.

B A flotation system using the pressurization and de-pressurization sequence consists of the following elements (Fig. 6).

1. Pressurizing pump
2. Air injection facilities
3. Retention tank or contact vessel
4. Back-pressure regulating device
5. Flotation device
6. Facility for addition of chemicals if needed


BACK PRESSURE VALVE
PRESSURIZED FEED
EFFLUENT
TOTAL PRESSURIZATION
UNPRESSURIZED PORTION OF FEED
FLOW BY GRAVITY OR PUMP
PORTION OF FEED WHICH HAS BEEN PRESSURIZED
EFFLUENT
BACK PRESSURE VALVE
PARTIAL PRESSURIZATION OF FEED
UNPRESSURIZED FEED
FLOW BY GRAVITY OR PUMP
PRESSURIZED EFFLUENT
EFFLUENT
BACK PRESSURE VALVE
PRESSURIZATION SEQUENCE
PARTIAL PRESSURIZATION OF EFFLUENT

METHODS EMPLOYED FOR PARTIAL AND TOTAL PRESSURIZATIONS

FIGURE 6

C Advantages and Disadvantages

1. Much reduced retention time - 10-20 minutes
2. Greater solids concentration in float than in settled sludge
3. Greater efficiency of solids recovery
4. Offers mechanical control over the process
5. Increased cost of operation for pumping, etc.
6. Need to remove top and bottom solids

IV SCREENING DEVICES

A Microscreening is a form of simple filtration by straining (Fig. 7).

1. These mechanical filters consist of a rotary drum which revolves on a horizontal axis. The peripheral surface of the drum is covered with a stainless steel fabric. The effectiveness of the woven mesh screen for retaining fine particles is dependent on the size of the openings in the screen and on the pattern of the weave.

2. Influent enters the open end of the drum and is filtered through the fabric with the intercepted solids being retained on the inside surface of the fabric. As the drum rotates, the solids are transported and continuously moved at the top of the drum by pumping strained effluent, under pressure, through a series of spray nozzles which extend the length of the drum. The solids and wash water are collected in a central trough within the drum and discharged through a hollow axle.

3. The microstraining device is available in several unit sizes ranging from 5' in diameter and 1' width with a capacity of 0.05 to 0.5 mgd to 10' diameter and 10' wide with a capacity of 3-10 mgd.

B Microscreening devices have found their greatest application to treatment of river waters, and information on their performance on wastewaters is quite scarce.

1 The effect of aperture size on removal efficiencies and flow rate is shown below.

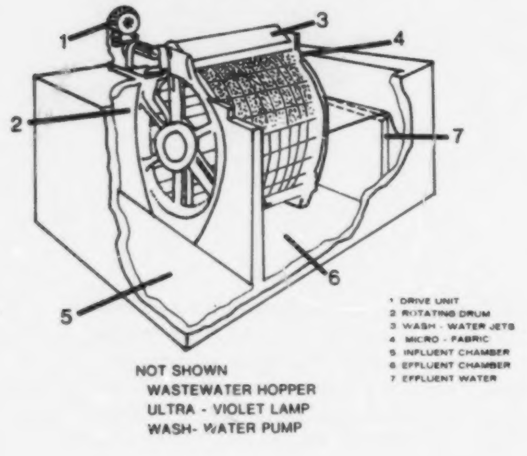
Fabric	Removal Efficiency		Flow
	Solids	BOD	gals/hr/ft^2
Mark O (23 microns)	70-80%	60-70%	400
Mark 1 (35 microns)	50-60%	40-50%	600

2 The advantages of microstraining are the low initial capital cost and ease of operation. The disadvantages are the incomplete solids removal and the inability to handle solids fluctuations.

3 The capital and operating costs associated with microstraining have been prepared by Smith and are shown in Fig. 8. For a 10 mgd plant, total cost for microstraining is calculated to cost about 1.5¢/1000 gallon.

FIGURE 7

TYPICAL MICROSTRAINER UNIT


1
2
3
4
5
6
7
1 DRIVE UNIT
2 ROTATING DRUM
3 WASH - WATER JETS
4 MICRO - FABRIC
5 INFLUENT CHAMBER
6 EFFLUENT CHAMBER
7 EFFLUENT WATER
NOT SHOWN
WASTEWATER HOPPER
ULTRA - VIOLET LAMP
WASH- WATER PUMP

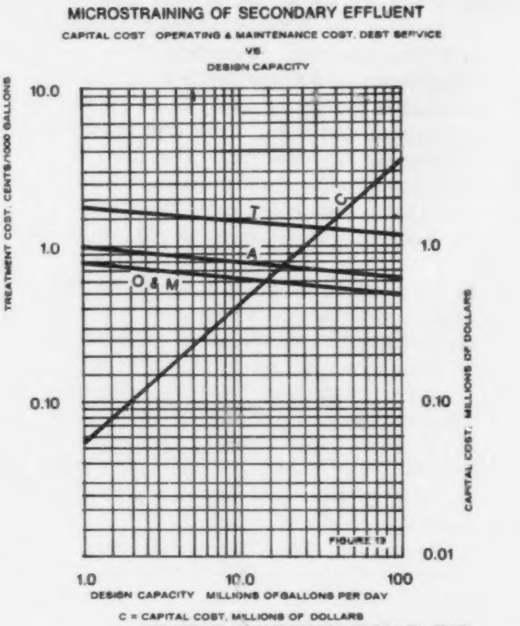


FIGURE 8

V IN-DEPTH FILTRATION

A In-depth filtration is the passage of a a fluid through a bed of granular media designed to permit the captured particles to be retained within the filter. The degree of penetration and solids removal efficiency can be altered by changing the size and character of the particulates to be removed as well as the size and composition of the filter media itself.

1 A basic prerequisite for the operation of rapid sand filters is that good coagulation and flocculation must be obtained. Barring adequate pretreatment of the wastewater, filtration efficiency is decreased as evidenced by "breakthrough" of floc. With good pretreatment by coagulation, higher filtration rates are attainable while still maintaining clarity of the effluent.

2 It is beyond the scope of this talk to discuss the subject of coagulation and flocculation. A variety of coagulants and flocculants are available including various salts of aluminum and iron, lime and organic polymeric flocculants. The former inorganic salts, in the proper dosages can also provide for precipitation of phosphate in addition to clarification.

3 In the past 70 or 80 years, there has been a gradual improvement in the basic process of media filtration. Some of the earlier work centered on increasing the filtration rates of slow sand filters to the modern rapid sand filter rates. Various cleaning methods were also developed including backwashing and surface scouring. More recently, the engineering advances have been concerned with modifications of filter media that would allow greater production of high quality water from a given filter area.

4 The evolution of filter design is illustrated in Fig. 9. The cross-section shown at the top represents the rapid-sand filter which is in common use in many filter plants today.

  a Typical effective size of the media used is 0.5 although effective sizes from 0.35 to 1.0 mm have been used.

  b During filter backwashing, the sand grades hydraulically with the finest particles rising to the top of the bed. As a result, most of the material removed by the filter is removed at very near the surface of the bed.

  c Only a small part of the total voids in the bed are used to store particulates and headloss increases very rapidly. When secondary effluent is being processed, the high solids concentration will blind the surface in a very short time. As much as 75-95% of the headloss, under these conditions, will occur at the upper 1-inch layer of the filter. Filter runs will be so short as to be prohibitive. Further, floc breaking through the topmost layers, have increased opportunity to pass through the entire filter since voids become increasingly larger with increase in depth.

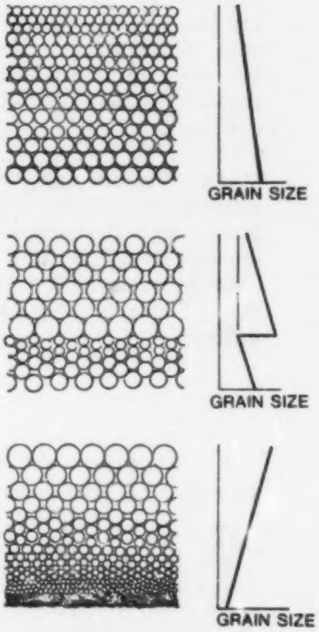


FIGURE 1
CROSS - SECTION THROUGH SINGLE - MEDIA BED SUCH AS CONVENTIONAL RAPID SAND FILTER

FIGURE 2
CROSS - SECTION THROUGH DUAL - MEDIA BED COARSE COAL ABOVE FINE SAND

FIGURE 3
CROSS - SECTION THROUGH IDEAL FILTER UNIFORMLY GRADED FROM COARSE TO FINE FROM TOP TO BOTTTOM

FIGURE 9

B One approach to increasing the effective filter depth is the use of a dual media bed using a discrete layer of coarse coal above a layer of find sand. The filter provides basically a two-layer effect to achieve increased penetration of particles.

1 The amount of sand is reduced to afford lower headlosses at the higher throughput rates used. Normally, such a bed is designed so that 24 inches of anthracite coal, with a nominal size of about 1 mm, overlays a 6 inch sand layer with a size of about 0.45 mm.

2 Hydraulic stratification still occurs following backwashing but the difference of specific gravity is such that the larger coal remains on top of the sand. The bulk of filtration is accomplished in the upper layers of the coal and at the top inch or two of the sand bed.

3 With low applied turbidities and constant rate operation, the coal-sand media bed has demonstrated an ability to operate in the range of 4-5 gal/min/sq ft of filter surface area.

4 A defect in this design is that if a flow change occurs, the particles held in the relatively large void volume of a coal bed, can become dislodged and will be captured by the fine layer of sand and the filtration run would have to be terminated either because of high head loss at the coal-sand interface or because of breakthrough of particles through the relatively shallow sand bed. This design, then, presents a serious inconsistency.

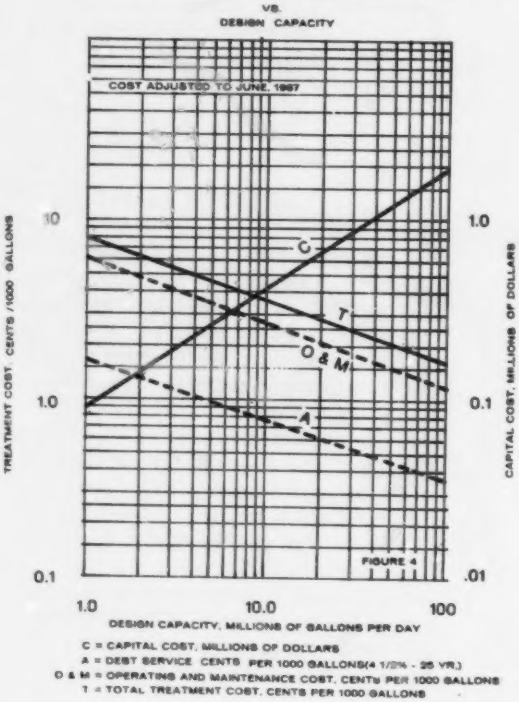
5 Ideally, the effluent should pass through as fine a filter material as is feasible. This ideal design is illustrated in the bottom cross-section of a filter uniformly graded from coarse to fine from top to bottom.

6 One solution is the use of three materials of differing specific gravity of such size gradation that some intermixing of the materials occur at the interfaces of the bed layers. The third media material is garnet which has a specific gravity of about 4.2. An ideal filter bed, then, would consist of about 60% of anthracite with a size of 1.0 to 1.5 mm at the top, 30% sand with a size of 0.4 to 0.5 mm at the middle and 10% of garnet with a size of about 0.15 mm. The materials are so sized that intermixing occurs at the interfaces. In this ideal filter, the effluent is passed through increasingly finer media. The uniform decrease in media particle size with filter depth allows the entire filter depth to be used for floc removal and storage.

7 Cost of the filtration step is shown in Fig. 10. For a 10 mgd plant this cost amounts to about 3.5¢/1000 gallon, when operating the filter at 4 gpm/sq ft. Further economy, of course, can be obtained at higher rates. Rates as high as 6-8 gpm/sq ft have been shown to be feasible when proper pretreatment of coagulation-flocculation followed by sedimentation is practiced.

FIGURE 10
FILTRATION THROUGH SAND
OR GRADED MEDIA - 4GPM/SQ FT

CAPITAL COST, OPERATING & MAINTENANCE COST, DEBT SERVICE
VS.
DESIGN CAPACITY



C Moving Bed Filter Technique

1 A new filtering technique has been evaluated by Johns-Manville under contract with FWQA. The technique is designed to overcome the problem of surface clogging and to achieve what is obtainable by multi-media filtration. A schematic diagram of the moving bed filter is shown in Fig. 11.

BASIC CONCEPT OF MOVING BED FILTER

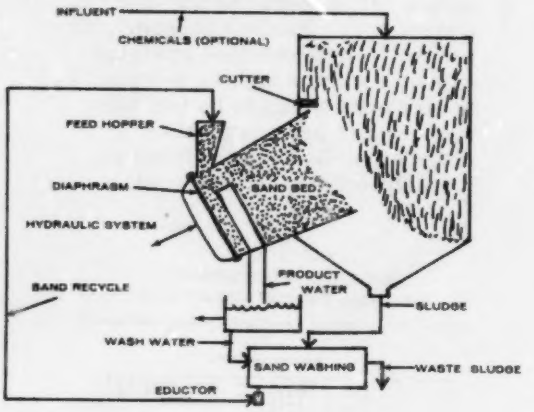


FIGURE 11

2 The unit is basically a sand filter. Particulate matter is removed as the water passes through the sand (0.6 to 0.8 mm). As the filter surface becomes clogged, the filter media is moved forward by means of a mechanical diaphragm. The clogged filter surface is removed either hydraulically or, as shown, mechanically thereby exposing a clean filter surface. The sand and accumulated sludge is collected and washed. The sand is returned via a hopper to the base of the bed. The unit is thus a form of countercurrent filtration device feeding sand countercurrent to the water being filtered. The moving bed filter has a renewable filter surface analogous to the microstrainer and the advantage of depth filtration comparable to the coarse media filter. The unit does not have to be taken off-stream for backwashing. In theory, 1% of the filter is being backwashed 100% of the time compared to the conventional practice of backwashing 100% of the filter 1% of the time.

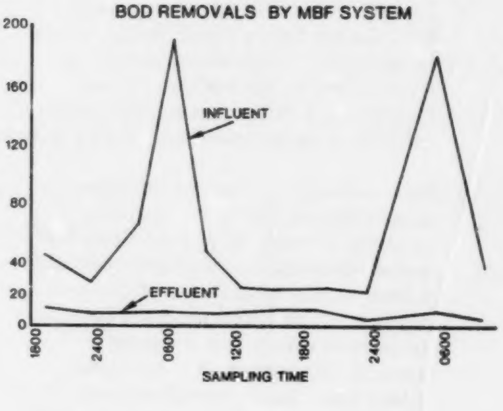
3 Several pilot MBF units have been built to date and used to treat settled and non-settled trickling filter effluents and primary effluent. The system lends itself well to the use of chemical aids ahead of filtration because of designed flexibility to handle high solids loadings.

Fig. 12 shows some data with the MBF treating non-settled trickling filter effluent with various dosages of alum and coagulant aid. Product quality was maintained at about 10 BOD while being fed an influent with a widely varying BOD content of 40 to as high as 180 BOD.

It is premature to talk about cost of this method of filtration. Design and performance information developed from these pilot units will be used to obtain these costs.

FIGURE 12

BOD REMOVALS BY MBF SYSTEM



VI ULTRAFILTRATION

A One of the newest unit processes to separate solids from liquids is the operation known as ultrafiltration. This method has been under development over the past 10 years, with commercial applications over the last 2 or 3 years.

1 Ultrafiltration is closely related to reverse osmosis with the distinction generally made on the basis of size of particle separated. Reverse osmosis removes molecular sizes including inorganic salts. Ultrafiltration generally will not separate molecules smaller than 500-1000 MW, thus inorganic salts are not separated from solution. Ultrafiltration uses pressures of about 50 psi in contrast to reverse osmosis where pressures in excess of 500 psi are generally used.

2 Membrane ultrafiltration is a pressure activated process using semi-permeable membranes which act as molecular screens to separate molecular and colloidal materials dissolved or suspended in a liquid phase.

3 Thus far, the principal commercial applications of the process have included:

a industrial operations where valuable products can be recovered by separation from a bulk solution,

b analytical application which provides a new method to separate molecules according to size and molecular weight, and

c in a package waste treatment plant which separates mixed-liquor solids from a biological reactor. Solids are returned to the aerator and clarified product water is discharged.

d A plant employing ultrafiltration has been installed on Pikes Peak to provide waste treatment and water reuse. The essentials of the process are shown in Fig. 13. The 15,000 gpd plant treats wastewater by high-solids activated sludge. The solids are separated in an ultrafiltration unit. Solids are returned to the aerator. Product water is excellent. Some typical removals are shown in the following:

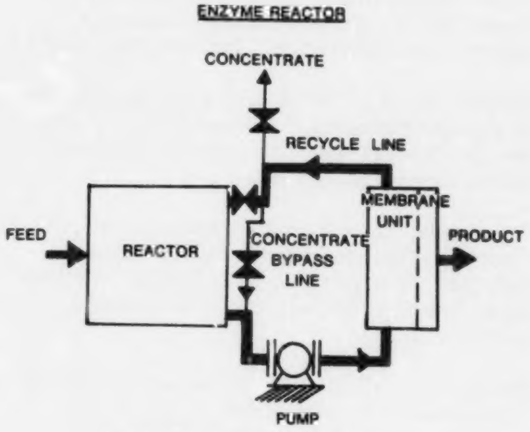


FIGURE 13 REACTION SYSTEM

REMOVALS BY ACTIVATED SLUDGE AND ULTRAFILTRATION

	Influent	Effluent	% Removal
BOD	382	< 1	> 99
COD	678	20	97
Turbidity	-	< 0.1	-
SS	323	0	100
PO_4-P*	12.2	7.7	37

*No added coagulants for P

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SEDIMENTATION BASINS IN WASTEWATER TREATMENT

I FUNCTION AND TYPE OF SEDIMENTATION BASIN

A Function

1 Grit removal

2 Primary sedimentation

  a Alone or in advance of other processes

  b With or without chemicals

3 Secondary sedimentation - following biological treatment

4 Sludge thickening

B Shape and Type

1 Horizontal flow - mechanical sludge removal

  a Rectangular

  b Circular

    1) Center feed

    2) Peripheral feed

  c Imhoff tank

  d Septic tank

2 Vertical flow

3 Tube settler[10]

II TYPICAL DESIGN CRITERIA

A Overflow Rates

Most State Standards specify maximum overflow rates in primary tanks of from 600 to 1,000 gpd per square feet with smaller plants using the lower rates. In secondary clarifiers, maximum overflow rates of 800-1,000 gpd per square feet are commonly specified.

B Detention Time

Some states set limits on both maximum overflow rate and minimum detention time. A figure of 2 hours' detention for primary tanks is common although shorter times are permitted for primary tanks ahead of activated sludge. For secondary tanks, 2 hours' detention is a common specification. The Ten State Standards do not specify detention times, but do set a minimum depth of 7 feet on primary and 8 feet on secondary tanks, which is tantamount for setting a minimum detention time, since

$$T = \frac{180\ D}{V_o}$$

where T = Detention time (hours)
D = Tank depth (ft)
V_o = Overflow rate (gpd per sq. ft.)

Thus, a tank with an overflow rate of 600 gpd per sq. ft. and a depth of 7 ft. has a detention time of 2.1 hours.

C Weir Loading

A number of states specify weir loading rates of the order of 10,000-15,000 gpd per lin. ft. of effluent weir.

D Other Criteria

Some states specify minimum distances from inlet to outlet, scum baffles are commonly required, and, as a rule, some requirement is set regarding even distribution of flow and dissipation of kinetic energy at the inlet.

III THEORY OF SEDIMENTATION

A Allen Hazen[1]

Hazen's paper published in the Transactions of the American Society of Civil Engineers in 1904 outlined the commonly accepted theory of settling of discrete particles in quiescent basins and discussed the effect of departures from ideal conditions. According to this theory sedimentation efficiency is a function of overflow rate and independent of depth.

B Thomas R. Camp[2]

Camp's paper on the Transactions of the American Society of Civil Engineers in 1946 elaborated on Hazen's theory, outlined the use of settling tube tests to determine the properties of suspensions, discussed settling of flocculent suspensions, scour of deposited materials, the effects of short circuiting and turbulence. He recommends the use of long shallow tanks for sedimentation with the depth being limited only by considerations of avoiding scouring velocities and the need for sludge removal equipment. This paper with the discussions that accompany it is probably the best single paper on the subject of sedimentation basin design.

Quote from the discussion of the paper.

E. Sherman Chase: ". . . . the design of practicable settling tanks will continue to be based upon judgment, experience, and common sense seasoned with a moderate amount of theoretical computations used as aids to judgment."

T. R. Camp: "This attitude has undoubtedly been that of most of the designers of tanks . . . . The moderate amount of theoretical computations which Mr. Chase suggests for seasoning the judgment has unfortunately been so moderate that it has been almost completely absent. Design has consisted almost wholly of conformity to previous practice in size and shape with little regard for the principles involved or for the nature and settling characteristics of the particles to be settled."

C E. B. Fitch[3]

Fitch, in Sewage and Industrial Wastes in 1957, makes the point that in dealing with flocculent suspensions a deep tank provides better opportunity for particle growth than a shallow one and hence that detention time cannot be discarded as a criterion in settling tank design. He also points out that hydraulic efficiency or absence of short circuiting is not necessarily important to good tank performance.

D Ronald T. McLaughlin[4]

McLaughlin, in the Hydraulics Division Journal of ASCE in December, 1959, points out how the properties of the suspension determine whether detention time, overflow rate, or both may be important to efficient sedimentation.

IV COMPLICATING FACTORS

A Flocculation

Most of the suspensions dealt with in wastewater treatment do flocculate. Exception - Grit. Extreme case - Activated sludge. Intermediate - Raw sewage.

B Flow Variations

The typical wastewater treatment plant is subject to wide variations in flow. It is virtually impossible to design a sedimentation tank that will behave in the same way hydraulically with flow varying by as much as a factor of 5-10 from maximum to minimum.

C Solids Removal

Sludge and scum removal mechanisms perturb somewhat the settling of suspended matter. It is necessary to consider a portion of the tank volume ineffective because of the operation of these mechanisms.

D Solids Concentration

It is commonly found that removal efficiency of sedimentation basins is higher when dealing with concentrated suspensions than when influent concentrations of suspended solids are low. It is not usually known why this is so. In some cases, it may be due to differences in the size distribution of the suspension. Many sewers act as crude settling basins which are periodically flushed out. At times of flush-out, this relatively coarse material reaches the treatment plant. High concentrations of suspended solids make for more effective flocculation as well. This accelerates settling.

E Inlet Design

A portion of any tank is ineffective for sedimentation because of need to dissipate influent kinetic energy and distribute flow evenly. In long tanks, the ineffective fraction of the tank is smaller than in short tanks. Flow variations and the necessity of avoiding small openings usually prevent the introduction of a controlling head loss to get even flow distribution.

F Density Currents

Virtually all tanks are affected by density currents. Activated sludge secondary tanks always have them, and most primary tanks have them from time to time. Anderson[5] has developed a design of secondary tank with an annular weir to improve efficiency of circular tanks. Gould in New York adopted another way of coping with density currents in rectangular secondary tanks. He places the sludge hopper near the effluent end of the tank instead of at the influent end.

G Resuspension of Deposited Solids

This limits acceptable horizontal velocities. Camp, using Shields formula, estimates that velocities as high as 7-8 fpm are acceptable. In primary tanks at Hyperion, there was evidence of resuspension when velocities exceeded about 4 fpm.[6] The presence of density currents can affect resuspension markedly. Burgess and his colleagues[7] studied flow patterns in the primary tanks of the Northern Outfall Works of the London County Council and found a very marked density current.

V PLANT PERFORMANCE

Comparatively few extensive studies of plant performance to guide engineer in design.

A NRC Study of Military Treatment Plants[8]

Studied 20 months of operating data from 18 primary plants. Mean BOD removal for the 18 plants ranged from 10 per cent to 61 per cent. Not only was there large variation between plants but also large variation in a given plant from one period to the next. Average detention period for the 18 plants was 3. 77 hours, average overflow rate was 506 gpd per sq. ft. Median displacement velocity was 0. 4 fpm. Detention period correlated more closely with removal efficiency than did overflow rate. There was no significant difference between circular and rectangular tanks, other things being equal. The following formula was used to fit the data for 10 plants where there was no recirculation to the primary tanks:

$$\text{Fractional Removal of Suspended Solids} = \frac{0.67\ T}{1 + 0.94\ T}$$

B Data in ASCE - WPCF Manual of Sewage Treatment Plant Design[9]

An analysis of data from 32 plants with rectangular primary tanks and 25 plants with circular primary tanks has been made. The following table shows data on size, loading, and performance at these plants:

	Rectangular Tanks		Circular Tanks	
	Mean	Std. Dev.	Mean	Std. Dev
Length or diameter ft.	118	53	88	32
Depth, ft.	10. 9	1. 85	10. 5	1. 98
Length/width	3. 77	1. 49	-	-
Detention time, hrs.	2. 53	1. 44	2. 65	1. 12
Overflow rate, gpd/ft^2	957	535	856	380
Influent suspended solids, mg/l	227	105	234	71
Effluent suspended solids, mg/l	106	60	89	33
% removal suspended solids	52. 6	15. 5	60. 8	11

Multiple correlation analysis were made on these data, using per cent removal of suspended solids as the dependent variable and various parameters as independent variables. There was little to choose between detention time and overflow rate as variables in predicting performance. There was no indication of marked superiority of one shape of tank over the other. As in the NRC study, there is a wide scatter of points about the fitted curve.

Equations fitted to the data were

Circular Tanks

$$\text{Fraction S. S. removed} = \frac{2.5\ T}{1 + 3.8\ T} \quad \text{and}$$

$$\text{Fraction S. S. removed} = \frac{2,940}{4,100 + V_o}$$

Rectangular Tanks

$$\text{Fraction S. S. removed} = \frac{.49\ T}{1 + .55\ T} \quad \text{and}$$

$$\text{Fraction S. S. removed} = \frac{1,350}{1,920 + V_o}$$

where T is detention time in hours

V_o is overflow rate in gallons per day per square foot.

C Secondary Clarifiers at Chicago Activated Sludge Plants

A secondary clarifier in an activated sludge plant is called upon to do a vastly more efficient job of solids separation than one expects of primary tanks. The influent contains thousands of mg/l of suspended solids and the effluent is expected to contain only tens of mg/l of suspended solids. Thus, we look for 99 percent or more removal of suspended solids. To achieve this, it is essential that the activated sludge be well flocculated and that only a small amount of the suspended solids be in small particles.

An analysis of two years operating data from five of the operating batteries at the three large Chicago activated sludge plants has been made to get some insight into the importance of various operating variables in determining plant performance.

The analysis showed clearly the superiority of the Anderson design with annular weirs over the older design with peripheral weirs. Overflow rate was not an important determinant of effluent suspended solids, although the five batteries had an average overflow rate of over 1,200 gpd per sq. ft. Temperature had a significant effect on clarifier efficiency. An organic loading parameter, pounds of BOD per day per pound of mixed liquor suspended solids, had a greater effect than either of the other variables.

The plants had average loadings of .19 pounds of BOD per day per pound of mixed liquor suspended solids with a range of monthly values of this parameter from .09 to .51. Effluent suspended solids for all of the plant units were 15 mg/l, with monthly averages ranging from 5 to 96 mg/l.

Sludge volume index was not a significant index of performance. It should be pointed out, however, that sludge volume indices were quite low, averaging 75 and varying from 46 to 139.

This analysis indicates that with well flocculated activated sludges excellent solids separation can usually be obtained at overflow rates considerably higher than those usually recommended. However, from time to time one must expect the system to get out of control and suspended solids carry-over in the effluent to occur.

VI CONCLUSION

In spite of the fact that theoretical considerations indicate that overflow rate should be a more significant parameter than detention time in design of sedimentation basins, plant performance data do not support the superiority of one design parameter over the other in plants with conventional depths.

Sedimentation basins generally show rather erratic performance in time. This is probably due at least in part to the inherent instability of flow patterns in basins with horizontal velocities low enough to prevent resuspension of deposited material. Flow fluctuations, changes in waste composition, wind, and solar radiation are other perturbing influences.

Although circular horizontal flow tanks are notoriously prone to short circuiting their performance in solids removal appears to be as good as that of rectangular tanks similarly loaded. The lower maintenance costs of sludge removal mechanisms in circular tanks is probably the most important factor in choosing between circular and rectangular tanks.

There is no rational basis for the relatively low overflow rates set by most of the state design standards. At small plants where the marginal cost of providing additional tank capacity is proportionately much less than in larger plants, there is probably not much reason to skimp on basin size, but in larger plants there may be significant economy in using higher rates. Overflow rates much higher than the conventional 800-1,000 gpd per sq. ft. are used in many plants with good efficiency.

There is little reason for maintaining low weir loading rates in primary tanks. In secondary tanks following activated sludge low weir loadings are important.

The tube settlers[10] that have been introduced recently have not as yet been tested enough for any conclusion to be reached as to their general usefulness in wastewater treatment. This development will be watched with interest.

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This outline was prepared by R. L. Woodward, Camp, Dresser and McKee Engineers, Boston, Massachusetts.

SEDIMENTATION TANK EQUIPMENT

I INTRODUCTION

The primary objectives of sedimentation equipment is the removal of settleable solids and floatable scum.

A Primary sedimentation objectives are to remove concentrated sludge without troublesome septicity.

B Secondary sedimentation requires prompt return of fresh solids with concentration as a secondary requirement.

C Basin, sludge collection, scum removal, drive mechanisms and available equipment will be discussed relative to A and B.

II SLUDGE COLLECTION EQUIPMENT

A General

Much equipment available, more similarities than differences. Three basic shapes of tanks: circular, rectangular, square.

B Circular Clarifier - Center Inlet

1 General

Most common flow pattern. Sewage enters center well, either through side of tank, or underneath and up. Sewage flows downward, then radially, over a peripheral weir.

2 Manufacturers

Infilco, Carter, Eimco, Yeomans, Dorr, Rex, Walker, Link-Belt, Hardinge.

3 Beam Supported Type

Scraper blades mounted on truss revolve about center shaft scraping sludge to central well. Supported from beams spanning tank. Full weight and torque carried by beams. For small tanks, usually 50 ft. in diameter or less. Motor driven at center. Skimmer connected to same shaft.

4 Center Column Type

For larger tanks up to 200 ft. diameter. Scraping mechanism similar to beam supported type. Scraper assembly suspended from a turntable carried by a central column. Rotated by means of motor driven gears mounted on a fixed bridge. Sewage enters up through hollow column, then flows radially.

5 Peripheral Drive

Center column. Rotating bridge drives scraping assembly. Driven peripherally by motor driven wheels on wall of tank. Not too common in New England. Snow and ice problems. Manufacturers: Infilco, Eimco, Walker.

6 Suction Type

For secondary sludge, mainly activated sludge. Suction pipes mounted on scraper truss. Suction created by hydrostatic head. Eimco, Dorr, Rex, Walker.

7 Radial Chain Scraper Type

Not common. Radially mounted endless chain type, scraping towards center while rotating. Peripheral drive. Link-Belt.

C Circular Clarifier - Peripheral Inlet

Sewage enters tangentially into a peripheral race. Skirt extends to 18" from floor. Sewage flows under skirt, then upward and over central weir. Scum, in theory, remains in raceway. Sludge removal equipment bridge supported. Lakeside, Yeomans, Rex.

D Rectangular Tanks

1 General

Sewage enters at end, is baffled, flows longitudinally to other end, out over weir.

2 Standard Chain Type

Oldest type. Chain and sprocket type. Flights attached to chains run on rails. Scrape sludge to hopper at inlet end. Cross collectors provided in hoppers of large tanks. Rex, Walker, Link-Belt, Yeomans, Jeffrey.

3 Moveable Bridge Type

Bridge spans tank width, running on rails. Rakes hung from bridge contact floor and move sludge to end of tank.

a Traction drive

Motor mounted on bridge. Electricity supplied by reel and cable. Hardinge, Link-Belt, Rex, Komline-Sanderson.

b Cable drive

Stationary drive at end of tank. Pulls cables attached to moving bridge. Dorr.

E Square Tanks

Flow can be center inlet, peripheral weir; or straight across flow. Mechanism similar to circular tanks except for extension arms which reach into corners, and scrape sludge back to normal radius of scraper. Not common. Dorr, Walker, Link-Belt, Rex.

III SCUM REMOVAL MECHANISMS

A Circular Tanks (Primary)

Skimming device rotates on center shaft. Details vary, but all types force scum towards periphery where it is deposited in scum box. Flows or is flushed to scum pit. Peripheral feed: Scum in raceway flows to a tilting skimming pipe. Incomplete removal. Scum still rises in main settling tank.

B Rectangular Tanks (Primary)

Return flights travel the surface forcing scum to end. Usually picked up in a revolving skimming pipe. Other types.

C Secondary Tanks

It is not standard practice to install scum removal mechanisms on secondary tanks. However, observations in Northeast Region leads us to believe that they are needed. We have been thinking of making this a firm requirement.

IV DRIVE MECHANISMS

Slow speed of rotation requires a large speed reduction ratio. Various types of reducers and gearing arrangements used, depending upon diameter (or length) of tank and sludge load.

This outline was prepared by S. C. Peterson, Chief, Construction Grants Activities, Region I, OWP, EPA, Boston, Massachusetts.

SETTLING TANK OPERATION

I INTRODUCTION

The purpose of the settling tank is to remove settleable solids and floating solids. Primary and secondary clarifiers are of three basic types: rectangular with mechanical collectors, circular with mechanical collectors, and non mechanically cleaned hopper bottom tanks.

II SCUM REMOVAL

A Operation

1 The objective in the operation of the skimmer or scum trough is to get the thick scum into the scum pit, while keeping the surface of the clarifier free from floating solids.

2 Reducing the amount of the scum which will be pumped to the digester should be considered. It will help to pump the scum back ahead of the comminutor thus grinding it and giving it another chance to settle out in the tank.

3 The skimmer should be hosed and swept clean daily. The scum pit should also be cleaned out after each pumping.

4 Removal of scum from the scum pit should be effected daily.

5 Crank case oil should be separated and buried. Under no condition should it or similar material be pumped to the digester.

B Excessive Scum Formation

1 Industrial wastes are frequently the cause of considerable quantities of floating solids. Pretreatment screens are often removed and when evidence of this condition occurs, the industry should be contacted.

2 Inadequate scum removal often results from the gasification and subsequent rising of sludge and will be treated under sludge removal.

3 In circular mechanically cleaned clarifiers the skimming belting often warps out of shape and ineffectively moves the scum. Whenever the belting fails to do a good job, it should be replaced.

4 Septic sewage devoid of dissolved oxygen will cause gasification of the particles settling and much of the incoming sludge will float. This will be treated under testing and interpretation of control.

III SLUDGE REMOVAL

Sludge removal not only affects the quality of the effluents from the primary and secondary treatment units, but also is a most important feature in the operation of the digester.

A Pumping periods must be frequent enough to prevent gasification of sludge in the hoppers, but periods must not be so frequent that sewage instead of sludge is pumped to the digester.

B If the slopes of the sludge hopper are not sufficient, sludge may adhere to the slope. Plants which have hopper slopes less than 1.4 vertical to one horizontal will probably find that it is necessary to rod the hoppers to keep the sludge from sticking.

C Sludge pump should have some method of varying the speed or pumping rate and should be set to pump less than 50 gallons a minute. If the pumping rate is too fast sewage will be pumped through a hole in the sludge blanket in the hopper and the sludge on the side of the hopper will remain there until it gasifies and rises in chunks.

D Practice of pumping more water (a thin sludge) to the digester than is actually needed will cause the digester to operate unsatisfactorily; because there is so much water, there is not enough room for solids.

E The daily variation in the strength of sewage will cause an increase or reduction in the quantity of solids deposited as sludge. It is often necessary to run settleable solid tests on the raw sewage through a 24-hour period to get a 24-hour picture of the variation of solids loading.

F Maximum duration of pumping should be figured and at no single pumping period should the total gallons pumped be greater than the capacity of the hoppers in gallons.

G Every plant should be able to see or sample the raw sludge. This is the best guide to obtaining a thick sludge. However, many experienced operators have never taken the time to run enough percent solid tests to train their eyes so that they can tell what a thick sludge really is. If possible, stop pumping when the sludge contains less than 4% solids.

H Supernatant solids entering a primary clarifier will necessitate extra pumping time. It is desirable to turn a supernatant high in solids to the drying bed rather than to allow it to return and upset a primary clarifier.

I Quantities of sludge can be estimated by running the settleable solids tests on the influents of the settling tank. For example at a flow of 150,000 gallons per day in the settleable solids of 6 ml/1 in the raw sewage, the non compacted sludge would be about .006 × 150,000 gallons equals 900 gallons of sludge to be pumped once daily.

J Considerable compaction can be effected in the hoppers of the clarifier if the size indicates that the sludge can be left in the hoppers for a longer period of time without becoming septic. On a once a day pumping schedule, it may be found that about one half of the theoretical amount of sludge figured under Part 9, can be pumped into the digesters and leave the the hoppers empty.

K Time clock operation is often necessary where the hopper capacity is limited if the effluent DO indicates that the sludge cannot remain in the clarifiers for a longer period of time. Hourly pumping can be estimated by the settleable solid tests taken at hourly intervals during the 24-hour period as mentioned under Part 5. It is also possible to set the time clock to pump 1/2 the calculated theoretical amount of sludge and then remove the excess sludge at two manual pumping periods during the day.

IV WEIRS, BAFFLES AND LAUNDERS

Weir placement, adjustment and maintenance govern the fraction of tank volume and surface available for clarification.

A Cleaning--The weirs scum baffles and launders should be hosed and scrubbed clean with a stiff broom daily. Weirs located at the ends of rectangular tanks occasionally have large particles of sludge going over the weir. This phenomenon is usually caused by solids creeping up the end of a tank which has a heavy growth on it. This creep can be minimized by keeping the scum baffles and weirs clean far below the water surface.

B Settling of the tank structure often causes weirs to allow more water to flow over one portion of the tank than over another. Most weirs are bolted through slots to permit leveling. When adjustments are made the operators should arrange to have a transit or level available to set the weirs properly. A weir which is not level will result in short circuiting.

C Occasionally weirs are not of sufficient length to accommodate the necessary flow. For every 10,000 gallons of sewage daily, it is necessary to have one foot of weir length or more.

D Baffling is necessary especially in rectangular tanks in order to prevent short circuiting. Stratification often occurs in such tanks due to difference in temperature of sewage at the top or bottom of the tank and it becomes necessary to deflect the thermal currents by baffling. In the winter it is sometimes necessary to put a baffle at the head of the tank to get the warm sewage to drop down to the bottom of the tank and under the baffle.

E Occasionally the channel carrying the clarified liquid which has passed over the weirs will have insufficient capacity to carry the necessary quantity of sewage, which will back up and submerge the weir. This may be due to defects in the design of the launder itself or in the piping. Additional pipe or channel capacity may be necessary for relief.

V CONTROL

Factors Affecting Control

A Detention Period--Most primary treatment units will operate satisfactorily with detention periods from 1 1/2 to 3 hours. Cold weather and the resulting low temperatures increase the viscosity of the sewage and settling is much slower. With a long detention period and summertime high temperatures, the plant's efficiency may be reduced by a septic sewage condition. This condition is brought on by the fact that at higher temperatures, oxygen absorption into the sewage is slow and the bacterial rate of using up the oxygen is accelerated.

B Overflow Rate--When a plant has the flexibility designed into it to permit operation of more than one primary settling tank, it is necessary to try to operate a clarifier at a satisfactory surface loading. The average plant will operate satisfactorily at surface loading of between 600 and 900 gallons per sq ft per day.

C Temperature of Sewage--Temperature has a pronounced affect on the settling of sewage. In cold weather, there is usually an ample supply of oxygen and settling is retarded by the viscosity of the sewage. In the summertime the viscosity of the sewage is low, but there is usually the lack of dissolved oxygen and the solids start to digest, producing gas bubbles which attach themselves to the sludge particles and lift them to the surface of the clarifier.

This outline was prepared by J. A. Montgomery, Sanitary Engineer, FWQA Manpower and Training Activities, PNWL, Corvallis, OR.

PRIMARY CLARIFIER CONTROL CHART

Effluent Settleable Solids In ml/1	Dissolved Oxygen Influent	Effluent	Condition	Probable Cause	Remedy
T-.3	Over 2.0	Over 2.0	Excellent		
T-.3	Over 2.0	2.0-.1	Fair	Warm or strong sewage	1, 2, 3
T-.3	Over 2.0	0	Unsatisfactory	Warm or strong sewage	1, 2, 3
T-.3	2.0-.1	Over 2.0	Good	Cold or weak sewage	
T-.3	2.0-.1	2.0-.1	Poor	Stale raw sewage	1
T-.3	2.0-.1	0	Unsatisfactory	Warm stale strong sewage	1, 2, 3
T-.3	0	Over 2.0	Good	Septic cold or weak sewage	4, 5, 6
T-.3	0	2.0-.1	Poor	Septic sewage	2, 4, 5, 6
T-.3	0	0	Very Bad	Warm strong septic sewage	1, 2, 3, 4, 5, 6
Over .3	Over 2.0	Over 2.0	Poor	Too much sewage	7
Over .3	Over 2.0	2.0-.1	Poor	Too much strong sewage	7, 2, 3
Over .3	Over 2.0	0	Unsatisfactory	Overloaded hydraulically and Organically	2, 3
Over .3	2.0-.1	2.0	Poor	Too much stale cold sewage	7
Over .3	2.1-.1	2.1-.1	Poor	Too much stale sewage	2, 7
Over .3	2.1-.1	0	Unsatisfactory	Too much stale or warm strong sewage	2, 3
Over .3	0	Over 2.0	Fair	Too much septic cold sewage	7, 4, 5, 6
Over .3	0	2.1-.1	Unsatisfactory	Too much septic sewage	7, 2, 4, 5, 6
Over .3	0	0	Terrible	Many reasons	2, 3, 4, 5, 6

REMEDY:

1. Increase flow to primary clarifier.
2. Prechlorinate so that no chlorine residual is in the effluent.
3. Add aeration or recirculation high in D.O.
4. Add upsewer chlorination so that no chlorine residual in plant influent.
5. Flush sewers routinely.
6. Move sewage rapidly through lift station.
7. Decrease flow to primary clarifier.

DISSOLVED-AIR FLOTATION

I INTRODUCTION

A Dissolved-air flotation was used first in industry for the removal of suspended matter in waste water arising from manufacturing operations. The method of dissolved-air flotation is applied to remove suspended matter from paper wastes, (1) refinery wastes, (2, 3) laundry wastes, (4) soap wastes, (5) machine shop wastes, (6) and others (2, 7) prior to discharge in a receiving stream or body of water or prior to reuse of the water and/or recovered suspended matter. In recent years, the process has been adapted to domestic waste water and sludge treatment. The process achieves the separation of suspended particles by attachment of gas bubbles to the suspended particles, thereby reducing the effective specific gravity of the particles to less than that of water.

B The principles of dissolved-air flotation are as follows:

1 Pressurized aeration

2 Reduction of pressure and turbulence

3 Formation of air bubbles of suitable size

4 The flotation of suspended matter via air entrapment

5 Separation of the solids concentrate from the liquid

II THE PROCESS

A There are two main applications for dissolved-air flotation:

1 Flotation clarification, where the main objective is a desired effluent quality.

2 Flotation thickening, where the main objective is solids concentration in the floated material.

B Process variables are as follows:

1 Point of air introduction to the system. (The major difference among flotation systems which are now available is the method by which air is introduced into the system.)

a Dissolved directly into the waste flow which is pumped to the flotation unit.

b Dissolved in a portion of the effluent from the flotation unit and prior to mixing with the raw waste.

2 Ratio of air charged stream to the raw waste flow.

3 Pressure maintained during pressurized aeration.

4 Sludge blanket depth carried on flotation unit.

5 Speed of skimmer of floated sludge blanket.

6 Flotation with chemical aids.

7 Flotation without chemical aids.

8 Type of raw waste floated.

a Primary waste sludge

b Activated waste sludge

c Combination of primary and activated waste sludge

d Paper wastes

e Refinery wastes

f Laundry wastes

g Soap wastes

h Machine shop wastes

i Algea growth collection

j Packing house grease waste

9 Particle rise rate of sludge particles

10 Surface loading rates

11 Air used per unit of pressurized liquid flow

C Operational Advantages:

1 Greater rates for de-watering sludges

2 Not adversely affected by the possible production of decomposition

3 Greater solids concentrations are attainable

4 Greater efficiency in solids recovery

5 Detention times are very short

6 Can possibly operate as a closed system eliminating a hydraulic load being returned to the plant

7 Offers some mechanical control over the process

8 Floated material from flotation unit has a greater amount of organic matter available for incineration or digestion.

D Operational Problems

1 Excessive loading may favor unduly thick sludge blankets that adversely affect separation of solids concentrate and clarified liquid.

2 Grit accumulation may require both top and bottom solids removal.

3 Good performance means control of a system of solids and associated air globules that will encourage flotation separation from the clarified liquid. The following variables are important:

a Mixing of air charged flow with the inlet stream.

b Control of skimmer depth and speed

c Control of the balance between solids loading and pressurized air.

d Control of chemical aids in process

III SUMMARY

A As with all waste treatment processes, flotation does not have universal application. Where flotation is applicable, the detention times which are used in flotation are much less than those used for sedimentation for obtaining equivalent results. Generally, the design detention time required for flotation varies from ten to thirty minutes. This range of detention time is in common practice low for sedimentation. The advantages of flotation are more apparent in systems where the subsidence values of the suspended material are extremely low and the solids are susceptible to dissolved-air flotation.

B Very conclusive plant studies should be conducted at least on the pilot plant basis before any design work is completed on full scale units.

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This outline was prepared by Carlos L. Doyle, Sanitary Engineer, Liquid Waste Disposal Division, 2700 S. Belmont Avenue, Indianapolis, Indiana 46221.

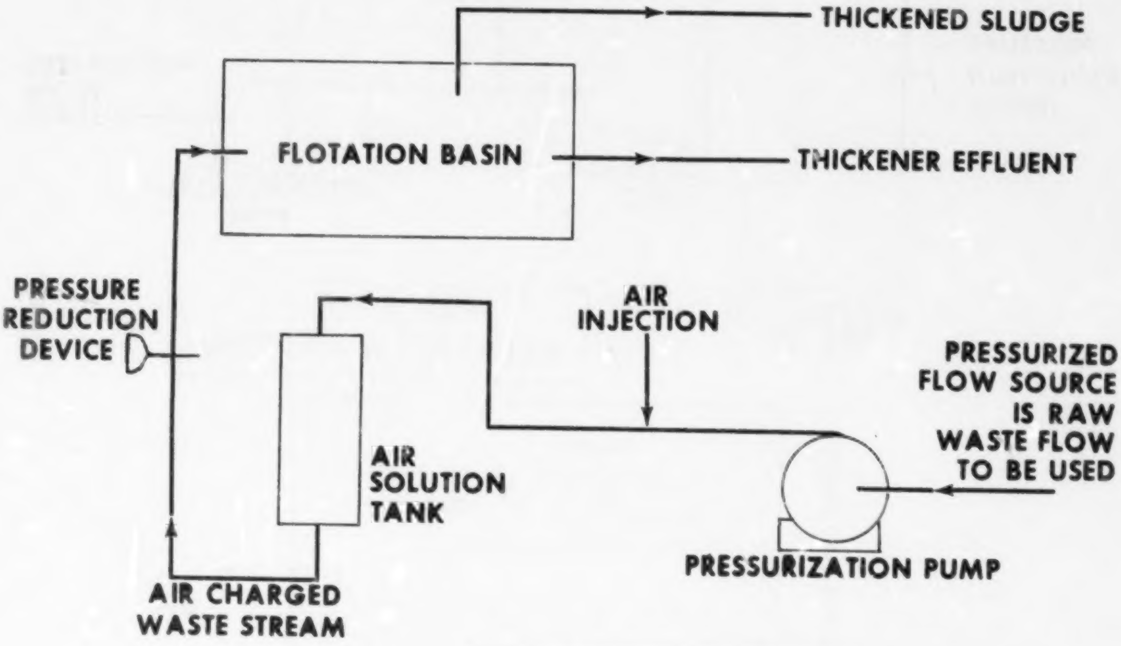

THICKENED SLUDGE
FLOTATION BASIN
THICKENER EFFLUENT
PRESSURE REDUCTION DEVICE
AIR INJECTION
PRESSURIZED FLOW SOURCE IS RAW WASTE FLOW TO BE USED
AIR SOLUTION TANK
PRESSURIZATION PUMP
AIR CHARGED WASTE STREAM

FIG. 1 BASIC FLOW PATTERN

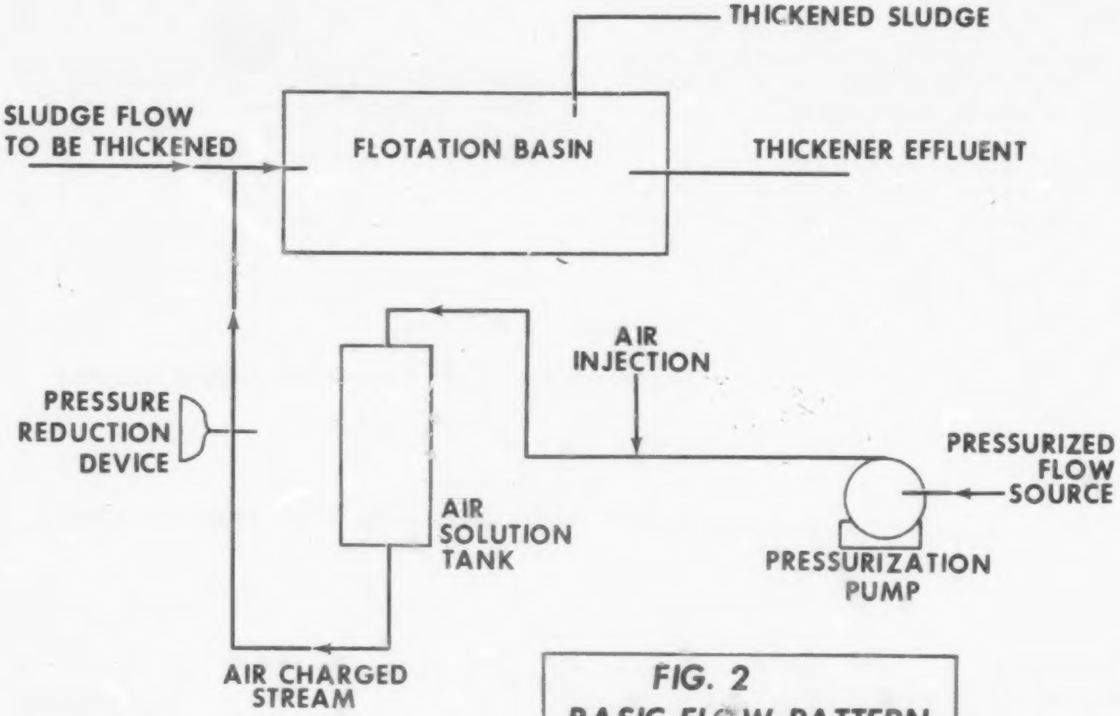

THICKENED SLUDGE
SLUDGE FLOW TO BE THICKENED
FLOTATION BASIN
THICKENER EFFLUENT
AIR INJECTION
PRESSURE REDUCTION DEVICE
PRESSURIZED FLOW SOURCE
AIR SOLUTION TANK
PRESSURIZATION PUMP
AIR CHARGED STREAM

FIG. 2
BASIC FLOW PATTERN

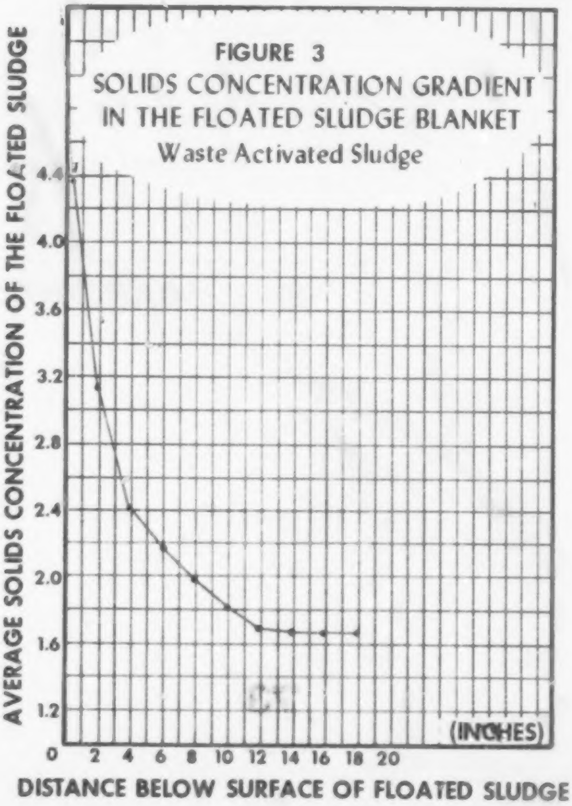
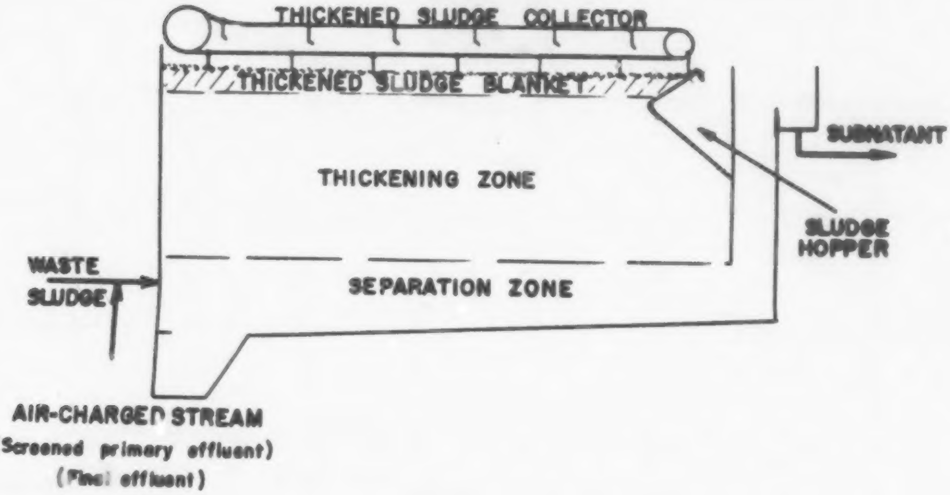
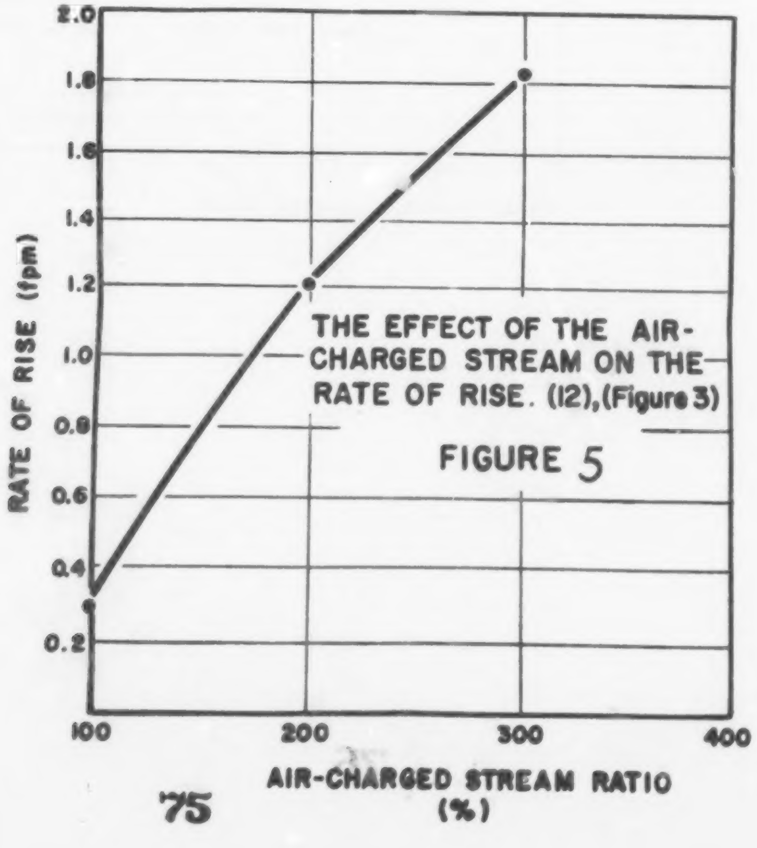


FIGURE 3
SOLIDS CONCENTRATION GRADIENT IN THE FLOATED SLUDGE BLANKET
Waste Activated Sludge

A FLOW DIAGRAM OF A DISSOLVED-AIR FLOTATION SYSTEM

FIGURE 4


THICKENED SLUDGE COLLECTOR
THICKENED SLUDGE BLANKET
THICKENING ZONE
SEPARATION ZONE
SUBNATANT
SLUDGE HOPPER
WASTE SLUDGE
AIR-CHARGED STREAM
(Screened primary effluent)
(Final effluent)

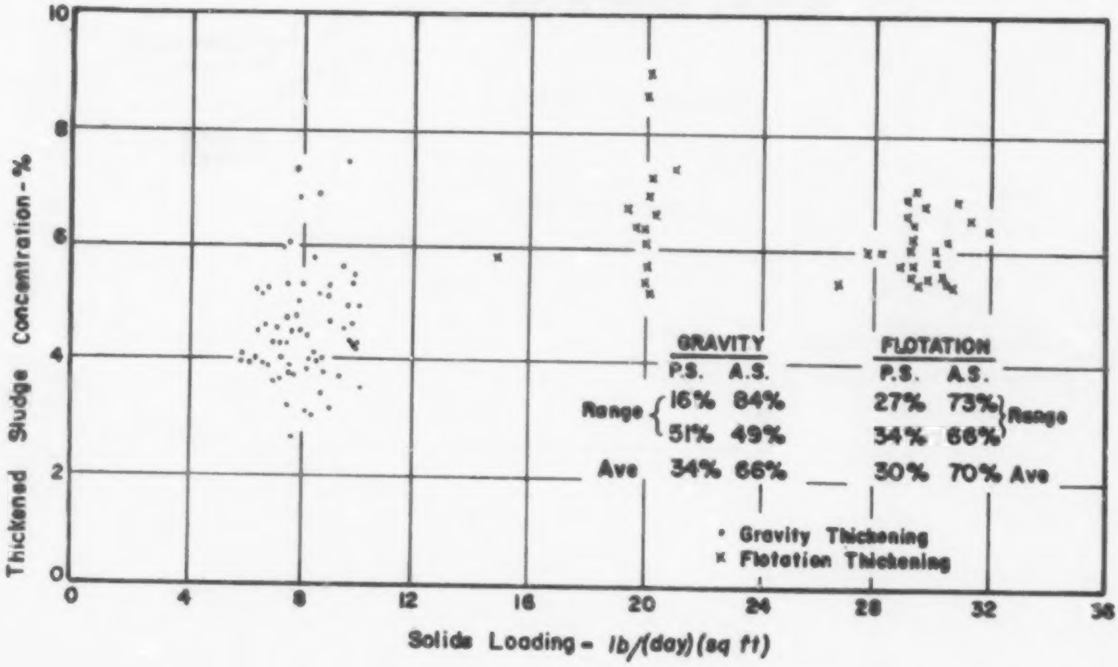


THE EFFECT OF THE AIR-CHARGED STREAM ON THE RATE OF RISE. (12),(Figure 3)

FIGURE 5

COMPARISON OF GRAVITY THICKENING AND FLOTATION THICKENING OF MIXTURES OF ACTIVATED AND PRIMARY SLUDGES

FIGURE 6



CHAPTER 12

SLUDGE DEWATERING

12.1 Vacuum Filtration

In 1967, there were slightly more than 1,500 vacuum filter installations in the United States in wastewater treatment service (1). The majority of these installations are in the larger municipal plants, where scarcity of available land often places sludge drying beds in an unfavorable economical position. The high degree of operator skill required for efficient vacuum filter operation is more likely to be available at larger plants than at smaller plants. Another factor which discourages extensive use of vacuum filters for sludge dewatering at small plants is the requirement for sludge conditioning prior to filtration. Small plants often do not have the necessary storage and handling facilities to purchase conditioning chemicals in economical bulk quantities.

12.1.1 Process Considerations

Process operating considerations for vacuum filtration include:

1. Control of feed solids concentration.
2. Chemical requirements for sludge conditioning.
3. Sludge mixing and flocculation.
4. Drum speed and drum submergence.
5. Filter fabric characteristics.

Each of these parameters affects the filter yield, economy of operation, and filter cake characteristics. The feed solids concentration can be controlled by pre-thickening the sludge. In general, the higher the feed solids concentration, the higher the filtration rate and the filter yield. The relationship is not linear, however, as was noted at one installation where doubling the feed solids concentration more than doubled the filtration rate (2).

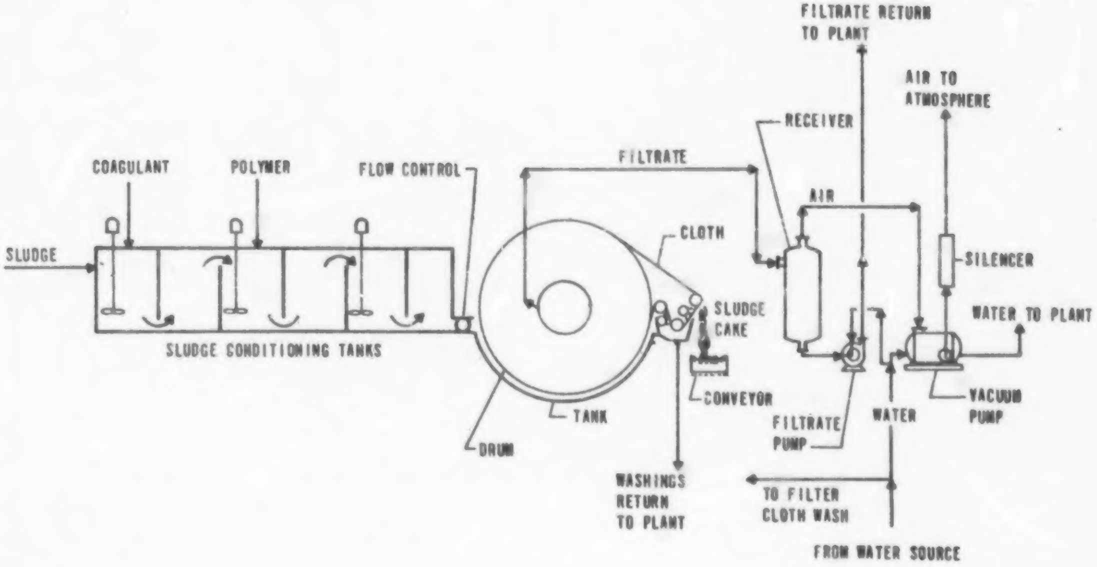
Few, if any, raw or digested wastewater sludges can be successfully dewatered without some form of chemical conditioning using ferric chloride, lime, and/or polyelectrolytes. Proper sludge conditioning requires a determination of optimum chemical dosages. Experience and careful laboratory monitoring of the sludge characteristics are key factors in maintaining the proper chemical proportions and concentrations.

Optimum sludge mixing and flocculation under varying conditions require that sludge conditioning tanks be provided with variable-speed mixer drives, removable weirs to vary the sludge detention time, and multiple points of chemical application as indicated in Figure 12-1. The sludge slurry must be agitated sufficiently to maintain uniformity; however, excessive agitation should be avoided so that the conditioned slurry particles are not sheared and broken up.

This copy taken from the "Process Design Manual for Upgrading Existing Wastewater Treatment Plants" prepared by Roy F. Weston, Inc. under Contract 14-12-933 with the EPA Technology Transfer Program.

FIGURE 12-1

TYPICAL VACUUM FILTER FLOW DIAGRAM


FILTRATE RETURN TO PLANT
AIR TO ATMOSPHERE
RECEIVER
FILTRATE
COAGULANT
POLYMER
FLOW CONTROL
AIR
CLOTH
SILENCER
SLUDGE
SLUDGE CAKE
WATER TO PLANT
SLUDGE CONDITIONING TANKS
CONVEYOR
VACUUM PUMP
FILTRATE PUMP
WATER
TANK
DRUM
WASHINGS RETURN TO PLANT
TO FILTER CLOTH WASH
FROM WATER SOURCE

Drum speed and drum submergence are important factors in the operation of vacuum filters since they affect filter yield and filter cake moisture. Increasing the drum submergence generally results in increased filter yield, but produces a filter cake with higher moisture content. Decreasing the drum speed, i.e., increasing the cycle time, has the opposite effect of decreasing the filter yield, but produces a cake with lower moisture content.

Much information is available from the various manufacturers of vacuum filters and filter media on the selection of a proper medium. The range of filter fabrics available for metal-belt or coil-type filters is limited when compared with the great number of cloths available for use with conventional drum or belt-type filters. Laboratory experimentation, using the Filter Leaf Test, provides information on filter farbic blinding, cake discharge characteristics, and filtrate quality, which is of use in selecting the best fabric for a given sludge.

12.1.2 Evaluation of the Vacuum Filtration Process

Experience has shown that there are considerable variations in filtration rate, not only between different sludge types, but also between the same types of sludges at different locations. The discrepancies in filter test results at different plants are usually related to variations in feed solids concentrations, particle size distributions, industrial waste components in the raw wastewater, etc. Obviously, then, it is of major concern to have a laboratory technique which can accurately predict the performance of a full-scale vacuum filter prior to its installation.

The Buchner Funnel Test and the Filter Leaf Test are commonly used in laboratory testing programs for estimating the filterability of sludges. When the amount of representative sludge is limited (less than 10 liters), it is advisable first to perform the Buchner Funnel Test to determine optimal chemical dosage and sludge filtration characteristics. The Filter Leaf Test can then be run at the optimum condition to determine filter yield. If a large amount of sludge is available, the Buchner Funnel Test can be eliminated and the Filter Leaf Test run instead.

The main purpose of the Buchner Funnel Test is to evaluate the optimum chemical requirements based on a comparison of the specific resistance of chemically treated sludge with that of untreated sludge. An approximate filter yield can also be calculated from the Buchner Funnel Test. Basically, the Buchner Funnel Test consists of filtering 100 ml of sludge, either raw or conditioned, through filter paper under a vacuum of 20 to 25 inches of mercury. The volume of filtrate (V, in ml) with time is noted and plotted against elapsed time/volume (t/V in sec./ml) to obtain the slope of the resulting line. Using the above information, the specific resistance of the sludge is calculated from the following equation:

$$r = 6.91 \times 10^6 \left(\frac{bA^2P}{\mu c}\right)$$

where:

r = Specific resistance, sec^2/gm
b = Slope of plot (V vs. t/V), sec/ml^2
A = Area of filter, sq.cm.
P = Filtration vacuum, psig
μ = Absolute viscosity of filtrate, centipoise
c = Initial suspended solids concentration, mg/ml

The dimensions of the variables in the above equation are in units typically measured in the laboratory. The conversion constant, 6.91×10^6, reduces the variables to units which are dimensionally consistent. The specific resistance as calculated by the above equation would be expressed as sec^2/gm.

The approximate filter yield can be estimated from the specific resistance data using the following relationship (3):

$$L = 0.0357 \left(\frac{100-C_f}{C_i-C_f}\right) \left(\frac{mPC_i\,(100-C_i)}{\theta R\mu}\right)^{1/2}$$

where:

L = Filter yield, lbs./sq.ft./hr.
C_i and C_f = Initial and final moisture content of the sludge, percent
m = Percentage of time for which vacuum acts during cycle
θ = Time for one drum revolution, minutes (usually between 1.5 and 5 minutes)
μ = Absolute viscosity of filtrate, centipoise
$R = r \times 10^{-7}$, gm/sec^2
r = Specific resistance, sec^2/gm
P = Filtration vacuum, psig

The Filter Leaf Test techniques are simple, and the test can be run with minimum effort. With careful laboratory techniques, results will be closely indicative of full-scale vacuum filter operation and need only be corrected by a design factor used to compensate for partial fabric blinding over a long period of operation. A scale-up design factor of 0.9 is typically used. The advantage of the Filter Leaf Test is that the filter yield is measured and not merely calculated using an empirical equation.

The Filter Leaf Test is usually performed on a 0.1 sq.ft. filter leaf. Different filter fabrics should be evaluated at a specified vacuum pressure. Varying doses and types of chemicals should also be tested to establish chemical conditioning requirements.

The main objective of the Filter Leaf Test is to evaluate the effect of different fabrics, fabric forms, and drying times on filter yield. The basic steps in performing a Filter Leaf Test consist of the following:

1. Submerge the filter leaf in the sludge slurry and apply vacuum for a fixed form time.

2. Remove the filter leaf from the sludge slurry to allow the cake to dry for a fixed drying time.

3. Remove the cake from the filter leaf and measure the weight and moisture content of the cake.

4. Measure the filtrate suspended solids to determine the filtrate characteristics.

The filter yield is then calculated using the following equation:

$$L = \frac{\text{dry sludge weight (gm) x number of filtration cycles/hr.}}{\text{453.6 x area of test filter leaf (sq.ft.)}}$$

where: L = Filter yield in lbs./sq.ft./hr.

12.1.3 Upgrading Existing Vacuum Filters

The need to upgrade an existing vacuum filter is usually due to an increase in the solids loading. Under these circumstances, existing vacuum filters are required to dewater at an increased filtration rate; otherwise, additional filtration capacity must be provided. The filtration rate of an existing vacuum filter can sometimes be increased by careful attention to operating conditions and judicious use of polyelectrolytes, where applicable, to improve sludge conditioning.

Most older filter installations were designed to use inorganic chemicals, such as ferric chloride and lime, as sludge conditioners. Within the last five years, organic polyelectrolytes have begun to replace inorganic chemicals as sludge conditioners, and these polymers offer an attractive advantage in more economical storage, handling, and feeding equipment. Polymers are also less corrosive and are frequently less expensive than inorganic chemicals within normal dosage ranges.

The yield obtained when using polymers in municipal sludge conditioning is generally higher than when using inorganic chemical conditioners. This statement is supported by studies conducted by the Dow Chemical Company (4) in which polyelectrolytes and inorganic conditioning chemicals were compared on the same sludges. The results shown in Table 12-1 indicate that polymer conditioning not only increases filter yield, but significantly reduces chemical requirements for conditioning sludge.

The use of polymers in improving the operation of vacuum filters has been practiced at treatment plants in Bay City, Michigan (5), and Kansas City, Missouri (6), among others.

The Bay City Wastewater Treatment Plant provides primary treatment for 7 mgd and produces approximately 450 tons of dry solids/year. Until 1961, raw primary sludge was

Table 12-1

Vacuum Filtration Results Comparing Inorganic Chemicals with Purifloc C-31 on Municipal Sludge

Location	Type of Sludge	Type of Filter	Filter Media	Chemical Conditioning	Dosage lbs./ton dry solids	Solids Concentration Initial percent	Solids Concentration Final percent	Filter Yield lbs./sq.ft./hr	Increase in Yield Due to Use of Polyelectrolytes percent
1. Municipal STP	Raw primary	K-S	coil	$FeCl_3$ Lime	162.4 166.8	7.57	20.1	6.91	
Municipal STP	Raw primary	K-S	coil	C-31	14.0	7.0	20.0	7.53	9
2. Municipal STP	Raw primary	K-S	coil	$Fe_2(SO_4)_3$ Lime	60 106	9.1	24.0	8.6	
Municipal STP	Raw primary	K-S	coil	C-31	8.4	9.6	20.0	11.5	34
3. Municipal STP	Raw primary	Eimco drum	open synthetic	$FeCl_3$ Lime	80.0 280.0	15	40.0	5.0	
Municipal STP	Raw primary	Eimco drum	open synthetic	C-31	18.0	12	30.0	7.0	40
4. Municipal STP	Raw primary	Eimco drum	open synthetic	$FeCl_3$ Lime	78.0 390.0	11.2	39.0	3.1	
Municipal STP	Raw primary	Eimco drum	open synthetic	C-31	20.0	10.7	34.5	3.5[1]	13
5. Atlanta, Clayton	Digested primary	D-O drum	long napped dacron	$Fe_2(SO_4)_3$	($6.06/T)	7.2	26.0	3.9	
Atlanta, Clayton	Digested primary	D-O drum	long napped dacron	C-31	($6.58/T)	7.2	33.5	11.0	182
6. Municipal STP	Digested primary	drum	44 x 44 saran	$FeCl_3$ Lime	66.0 206.0	15.0	43.0	9.2	
Municipal STP	Digested primary	drum	44 x 44 saran	C-31	17.0	15.0	32.0	25.0	172
7. Municipal STP	Elutriated/digested/primary	D-O drum	napped polyester	$FeCl_3$	56.8	6.1	36.0	5.74	
Municipal STP	Elutriated/digested/primary	D-O drum	napped polyester	C-31	10.2	7.7	32.9	12.66	121
8. Municipal STP	Elutriated/digested/primary	D-O drum	napped polyester	$FeCl_3$	100.0	10.4	32.7	3.88	
Municipal STP	Elutriated/digested/primary	D-O drum	napped polyester	C-31	8.0	10.1	38.6	5.94	53
9. Municipal STP	Elutriated/digested/primary	Eimco drum	napped polyester	$Fe_2(SO_4)_3$	108.0	10.9	34.0	2.8	
Municipal STP	Elutriated/digested/primary	Eimco drum	napped polyester	C-31	9.0	11.1	35.0	5.5	96
10. Atlanta - South River	Elutriated/digested primary and secondary	D-O drum	long napped dacron	Lime $Fe_2(SO_4)_3$ C-31	($8.90/T) ($8.79/T)	9.1 9.1	25.0 24.0	4.7 7.4	57
11. Municipal STP	Digested primary and secondary	Eimco	synthetic	$FeCl_3$ Lime	610.0(total) or ($10.07/ton)	4.4	26.2	5.2	
Municipal STP	Digested primary and secondary	Eimco	synthetic	C-31	18.0 ($6.12/ton)	4.3	23.7	5.6	8
12. Municipal STP	Elutriated/digested/primary and secondary	D-O drum	napped dacron	$Fe_2(SO_4)_3$ Lime	360.0 120.0	8.0	28.0	5.1	
Municipal STP	Elutriated/digested/primary and secondary	D-O drum	napped dacron	C-31	22.0	9.0	25.0	7.25	42

[1] Yield intentionally kept down to avoid overloading incinerator

Source: Dow Chemical Company (4)

conditioned with ferric chloride ($FeCl_3$) and either kiln-dried pebble lime or spent carbide (calcium hydroxide formed as the result of chemical action in making acetylene). Bay City's conditioned sludge is dewatered on vacuum filters having an effective area of 150 sq.ft. The vacuum filter cake is incinerated. In 1961, polyelectrolytes were tried as sludge conditioners in an attempt to improve filter yield. Results of filter operation for 1959-1964 using $FeCl_3$, lime, and polyelectrolytes (5) are presented in Table 12-2.

These results clearly indicate that use of polyelectrolytes increased the filter yield and significantly reduced vacuum filtration operation time.

The cost of chemicals for sludge conditioning was found to be $9.93/ton of dry solids using $FeCl_3$ and kiln dried lime, $6.85/ton of dry solids when using $FeCl_3$ and carbide lime, and $7.00/ton of dry solids when using polyelectrolytes.

The following advantages were realized at Bay City when polyelectrolytes were used for sludge conditioning.

1. Equipment and floor space savings.
2. Improved housekeeping.
3. Improved safety.
4. Reduced quantities of ash, with a large reduction in ash handling and storage.
5. Reduction in operating time, with resulting savings in operating and maintenance costs.

In Kansas City, 115 mgd of wastewater are treated in two plants, and the resulting sludge is pumped to a central location for sludge dewatering (6). Polyelectrolytes were selected for sludge conditioning in the dewatering operation. Dewatered sludge is incinerated. The specifications for sludge dewatering included: a filter capacity of 2,300 lbs./hr. for each of eight filters, a filtration rate of 6.2 lbs./sq.ft./hr. at minimum solids concentration, and a maximum moisture content of 75 percent in the cake. The cost of polymer conditioning was initially estimated at $4.30/ton of dry solids. During the first six months of operation, however, the actual cost of polymer was $10.61/ton dry solids. This cost was reduced by $2.20/ton of dry solids during the subsequent four-year period of operation.

Despite the higher than estimated cost for sludge conditioning, the experiences of the Kansas City Treatment Plant with polyelectrolytes have been satisfactory, since both the filter yield and cake moisture content specifications are routinely met.

One area where polyelectrolytes have not been as effective as inorganic chemical conditioning is in the vacuum filtration of waste activated sludge directly from the underflow of a secondary clarifier (without thickening). Preliminary information from an oxygen aeration study conducted at Batavia, New York, indicates that the optimum conditioning was ferric chloride at a dosage of 200 lbs./ton of dry solids (7). The waste activated sludge concentration from the oxygen aeration system varied between

Table 12-2

A Comparison Between Lime/Ferric Chloride and Polyelectrolytes for Conditioning Raw Primary Sludge

Year	Dry Solids	Solids in Feed Sludge	Filter Yield	Amount of Substance Added pounds						Solids in Cake	Solids Recovery	Operation Time
				Lime	$FeCl_3$	C-31	C-32	C-149	A-21			
	tons	percent	lbs./sq.ft./hr.							percent	percent	hours
1959	461	11.2	3.1	162.000	31.000	—	—	—	—	40.1	64.1	2,125
1960	580	11.2	3.1	225.000	44.000	—	—	—	—	39.0	62.1	2,420
1961-62	424	10.9	5.3	—	—	—	5.562	—	—	35.9	75.6	1,119
1962-63	415	10.7	5.5	—	—	10.300	—	—	—	34.5	73.7	1,114
1963-64	437	10.2	6.3	—	—	—	Total of all three polymers 7.671			34.6	75.9	1,301

Source: Sherbick (5).

2 and 3 percent. Filter yield increased from 1 to 5 lbs./sq.ft./hr. as the cycle time was decreased from 6 to 2 minutes/revolution. The moisture content varied between 75 and 85 percent, with the higher moisture content generally corresponding with lower cycle times. Likewise, in the City of Milwaukee, unthickened (diffused air) waste activated sludge is vacuum filtered using ferric chloride (8). The filter yield ranges between 1 and 3 lbs./sq.ft./hr. for an average cycle time of 3.5 to 4.0 minutes/revolution (cake moisture content 80 to 85 percent).

12.1.4 Process Designs and Cost Estimates

The following example will serve to illustrate design and cost considerations when upgrading vacuum filter installations by converting from inorganic chemical to polyelectrolyte sludge conditioning.

An existing vacuum filter installation annually conditions and filters 300 tons (dry basis) of mixed digested primary and secondary sludge with a filter yield of 5 lbs./sq.ft./hr. In the past, sludge conditioning has been accomplished using 65 lbs. of ferric chloride and 200 lbs. of lime per ton of dry solids. To reduce the costs involved in bulk chemical handling and to increase filter yield, the applicability of a polyelectrolyte system for sludge conditioning is investigated.

The optimum polyelectrolyte dosage is found to be 20 lbs./ton of dry solids, added to the digested sludge in a 1-percent solution. The polyelectrolyte addition results in a subsequent filter yield of 8 lbs./sq.ft./hr. This upgrading procedure enables the vacuum filter to decrease its operating time by over 60 percent, thereby decreasing operational and maintenance costs.

The capital cost for the polyelectrolyte application system is estimated at $6,000 (ENR Index 1500). This cost includes all required tankage, pumps, and mixers. In actuality, this cost is probably high since some of the equipment could probably be salvaged from the existing inorganic chemical addition system.

The available coagulants are not equally effective for sludge dewatering. Alum has been used successfully at a dosage of 1 lb. of alum per 100 gallons of digested sludge (1 . On the other hand, polyelectrolyte has been used at dosages as low as 0.05 lb. per 100 gallons of digested sludge (10).

In many parts of the country, the common practice is to cover sludge beds to protect them from rainfall and severe winter conditions. Recent work in northern Texas indicated that, during the dry season, covers retarded the drying rate rather than accelerating it (10). These data point to the fact that drying of sludge under covered conditions is not necessarily advantageous when weather conditions are more favorable for natural drying.

12.2.4 Process Designs and Cost Estimates

An open drying bed at an existing activated sludge plant was originally designed based on a population equivalent of 20,000 and a land requirement of 2 sq.ft./capita, and was loaded at a rate of 10 lbs. of dry solids/yr./sq.ft. As a result of upgrading secondary treatment units, it was necessary to increase the loading to 15 lbs./yr./sq.ft. to accommodate increased sludge quantities. Two alternatives were available for upgrading the existing drying beds. It was possible either to cover the beds and reduce the area requirements to approximately 1.35 sq.ft./capita, or to add 1 lb. of alum per 100 gallons of digested sludge to decrease the drying time by approximately 50 percent.

Covering the drying beds was estimated to cost $200,000, or $2,000/ton dry solids/yr. of increased cake yield (ENR Index 1500). The alum slurry feed system and flocculation tank was estimated at $28,000, or $280/ton dry solids/yr. of increased cake yield.

Based on comparison of these capital cost estimates for upgrading sludge drying beds, it would appear that chemical addition would be the most economic alternative provided that the climatic conditions would not adversely affect its operation. In order to make a definite conclusion, it would be necessary to compare yearly operating costs which would include chemical costs.

12.3 Centrifugation

Centrifuges have been used for many years by various industries for clarifying liquids, concentrating solids, separating immiscible liquids, and purifying oils. However, their use in the wastewater field for sludge dewatering is not as widespread as is the use of vacuum filters. Recent improvements in centrifuge design, efforts by the centrifuge industry to enter the wastewater treatment field, and broader dissemination of centrifuge performance data have encouraged increased use of centrifuges for thickening and dewatering of primary, secondary, and combined wastewater sludges. Centrifuges have good potential for upgrading overloaded solids handling facilities due to their flexibility in operation and lesser space requirements compared to vacuum filters.

This copy taken from the "Process Design Manual for Upgrading Existing Wastewater Treatment Plants" prepared by Roy F. Weston, Inc. under Contract 14-12-933 with the EPA Technology Transfer Program.

12.3.1 Types of Centrifuges

There are three general classifications of centrifuges that can be applied to sludge thickening and dewatering: solid-bowl, disc, and basket centrifuges. These are illustrated in Figure 12-2 (15). The capabilities of these units in processing wastewater sludges are summarized in Table 12-5 (16).

Table 12-5

Summary of Centrifuge Characteristics

Description	Centrifuge Description		
	Solid-Bowl Continuous	Basket Batch	Disc Continuous
Bowl diameter, in.	6 to 60	12 to 60	8 to 30
Flow rate, gpm	1 to 200	100 max.	10 to 300
Solids in feed, percent	*	0.1 to 30	0.1 to 10
Solids Discharged	1 to 15 tons/hr.	1,000 lbs.-max.	10 to 3,000 gal./hr.
Speed, rpm	1,000 to 6,000	2,500 max.	4,500 to 10,000
Centrifugal Force, G	3,200 max.	2,000 max.	12,000 max.
Motor horsepower	5 to 250	100 max.	10 to 125

*Any liquid or slurry which can be pumped.

Source: Townsend (16).

The most popular type of centrifuge today is the solid-bowl because of its dependable performance and low maintenance requirements. The solid-bowl machine has a spinning cylinder which causes particles to settle out along its inner wall. Solid-bowl centrifuges are especially suited to dewatering primary wastewater sludge and mixtures of primary and waste biological sludge. They are also able to dewater waste biological sludge alone, but some form of polymer addition is required in order to operate at an economical feed rate and to obtain solids concentrations above 5 or 6 percent. For most sludges, to achieve solids recovery in the range of 80 to 95 percent with a solid-bowl centrifuge requires the addition of polymers to the sludge.

The basket centrifuge is a tubular type centrifuge with a solid bowl and, therefore, is similar to the solid-bowl centrifuge in that the solids settle out along the inner wall due to centrifugal force. The solids are removed on an automated batch basis. Because of the large bowl diameter, the basket centrifuge is operated at slower speeds. The centrifuge can be operated on automatic cycle for programmed filling and skimming. Abrasion occurs only with the skimming tool. Hence, for the most part, this is a low-speed, low-maintenance unit.

The application of basket centrifuges to the wastewater treatment field is relatively new. Field tests of this unit have been successful in thickening waste activated sludge and indicate that this unit may be increasingly utilized in small plants to improve sludge dewatering operations. Concentrations of 9 to 10 percent solids can be produced, without the use of polymers, with solids recoveries of 80 to 90 percent.

The disc centrifuge utilizes a vertical disc stack, with subsequent sludge discharge through nozzles located around the periphery of the disc stack. The use of disc centrifuges for thickening in Sioux Falls, S,D. (17) and Chicago, Ill. (18) resulted in plugging of the disc stack and nozzles. It has been found that these problems can be minimized by using screens in the feed line to the centrifuge. Recently, it has been reported that disc centrifuges can increase the solids concentrations of waste activated sludge from 0.5-1.0 percent to a concentration of 5.0-6.0 percent without the use of polymers (17).

12.3.2 Process Considerations

Process variables for centrifugation are feed rate, sludge solids characteristics, feed consistency, temperature, and chemical additives. Machine variables are bowl design, bowl speed, pool volume, and conveyor speed (2). Major factors of importance in the product sludge are cake dryness and solids recovery. To increase cake dryness, the following guidelines are important (2):

1. Increase feed rate.
2. Decrease feed solids concentration.
3. Increase temperature.
4. Do not use flocculants.
5. Increase bowl speed.
6. Decrease pool volume.
7. Decrease conveyor speed.

Guidelines for increasing solids recovery are as follows (2):

1. Decrease feed rate.
2. Increase feed solids concentration.
3. Increase temperature.
4. Use flocculants.
5. Increase bowl speed.
6. Increase pool volume.
7. Decrease conveyor speed.

The above-mentioned guidelines indicate that most of the variables which improve cake dryness tend to decrease the solids recovery. This is an important feature of centrifuge operation. Therefore, operation of a centrifuge should be optimized to obtain the desired balance between cake dryness and solids recovery.

The following advantages are associated with the use of a centrifuge:

1. Capital cost is low in comparison with other mechanical equipment.
2. Operating costs are moderate, provided flocculants are not required.
3. The unit is totally enclosed so that odors are minimized.
4. The unit is simple and will fit in a small space.
5. Chemical conditioning of the sludge is often not required.
6. The unit is flexible in that it can handle a wide variety of solids and can function as a thickening as well as a dewatering device.
7. Little supervision is required.
8. The centrifuge can dewater some industrial sludges that cannot be handled by vacuum filters.

Disadvantages of its use are:

1. Without the use of chemicals, solids capture is often poor.
2. Chemical costs can be substantial.
3. Trash must often be removed from the centrifuge feed by screening.
4. Percent cake solids are often lower than those resulting from vacuum filtration.
5. Maintenance costs are high.
6. Fine solids which escape the centrifuge (in the centrate) may resist settling when recycled to the head of the treatment plant and gradually build up in concentration and eventually raise effluent solids levels.

12.3.3 Design Considerations

Centrifuges are usually selected on the basis of tests with smaller, geometrically-similar machines. The use of a continuous centrifuge for testing purposes is not realistic if sludge supply is limited, as when evaluating a small pilot plant. In the past, no laboratory procedure has been available to predict prototype performance. This is in direct contrast to the laboratory procedures, namely the Buchner Funnel Test and the Filter Leaf Test, which have been developed to assess the dewatering characteristics of the vacuum filter.

Recently, Vesilind (19) developed a laboratory procedure which makes it possible to predict prototype centrifuge performance on the basis of percent solids recovery. By trial and error, it was found that the following model relates laboratory to prototype data:

$$\text{Estimated Percent Recovery} = 100 \left(\frac{C_f - S}{C_f}\right)\left(\frac{P}{100}\right)^{0.1}$$

where:

C_f = Feed solids concentrations, mg/l
S = Centrate solids concentration, mg/l, measured after spinning in a laboratory centrifuge at a desired centrifugal force and appropriate time.
P = Percent of sludge not penetrated as determined from a sludge penetrometer.

No attempt was made to determine percent cake solids in this study. However, it is known that percent solids recovery and cake solids have an inverse relationship, i.e., the higher the solids recovery, the lower the percent cake solids. The numerical difference between predicted and actual solids recovery from Vesilind's formula can be expected to be within plus or minus 10 percent.

12.3.4 Centrifuge Performance in Sludge Thickening and Dewatering

Table 12-6 contains operating data supplied by various centrifuge manufacturers as well as that reported in the literature for various combinations of municipal wastewater sludges. These data indicate that the solid-bowl centrifuge is the most adaptable to the various combinations of wastewater sludges.

Raw primary and digested primary sludges dewater easily. With polymer addition, a centrifuge can produce 25 to 40 percent cake solids with better than 90 percent recovery. When trickling filter sludge is added to either of these sludges, the percent cake solids drops to 20 to 25 percent, and the polymer dosage to obtain 90 percent recovery increases. Factors responsible for this loss in efficiency include lower feed solids and the less favorable dewatering characteristics of biological sludge compared to primary sludge.

Waste activated sludge, by itself without conditioning, is difficult to thicken or dewater. This is readily evident in Table 12-6 and is not peculiar to the centrifuge process. A disc centrifuge can thicken waste activated sludge to 5 to 7 percent recovery without polymers. A basket centrifuge can also thicken waste activated sludge, but large amounts of polymer are required to make the sludge scrollable. To obtain 8 to 10 percent cake solids, polymers at a cost of $15 to $20/ton of dry solids are required to obtain greater than 90 percent recovery.

The use of centrifuges for sludge dewatering has been considered recently by several municipalities. At one large southeastern city, a centrifuge test program was conducted to determine the applicability of centrifuge dewatering of raw primary, digested primary, co-settled raw primary and waste activated, mixed digested, and primary digested plus thickened waste activated sludges (20). With a solid-bowl centrifuge, 55 to 85 percent recovery was obtained without the use of polyelectrolytes depending upon the feed rate. Recovery levels of 85 percent or better were achieved with 0.5 to 5 pounds of strong cationic polyelectrolyte per ton of dry solids for combined raw primary and waste activated sludges, primary digested plus waste activated sludges, and mixed digested sludges. Thickening of waste activated sludge using a disc machine was found to be feasible and produced 5 to 7 percent solids without polyelectrolytes. Problems were encountered in trying to use a solid-bowl centrifuge on the combination of thickened waste activated and primary digested sludges. Higher levels of polyelectrolyte were required as the proportion of activated sludge to primary sludge increased. When operating with a mixture of 2/3 primary digested sludge and 1/3 thickened waste activated sludge on a dry solids basis, 50 to 60 percent recovery was achieved without polyelectrolytes. To increase recovery to 80 to 90 percent, polyelectrolyte dosages of 10 to 20 pounds/ton of dry solids were required.

Table 12-6

Centrifuge Performance Data

Type of Sludge	Centrifuge Type	Capacity gpm	Percent Feed Solids	Percent Cake Solids	Percent Recovery	Polymer Requirement $/ton	Polymer Requirement lbs./ton	Reference
Primary - Raw	Solid Bowl			30-40	70-80		None	20
Primary - Raw	Solid Bowl			30-40	95		5-10	20
Primary - Raw	Solid Bowl			25-35	90+	2-4		20
Primary - Raw	Solid Bowl			28-40	70-90	None		20
Primary - Raw	Solid Bowl			30-40	50-90		1.5-2.5	20
Primary - Raw	Solid Bowl	23-26	9-12	28-50	65-80	None		20
Primary - Raw	Solid Bowl	23-36	9-12	28-50	80-98		1.0-2.5	20
Primary - Raw	Solid Bowl			32-37	84-93	6.4		21
Primary - Raw	Solid Bowl			25-28	88-95	3-5		21
Primary - Raw	Solid Bowl			26-37	85-96	2-7		21
Primary - Raw	Solid Bowl	27.5	8.8		44	None		23
Primary - Raw	Solid Bowl	27.5	8.4		84	3.94		23
Primary - Raw	Solid Bowl	27.5	9.2		97	5.72		23
Primary - Digested	Solid Bowl			30-40	70-90		None	22
Primary - Digested	Solid Bowl			30-40	95		5-10	22
Primary - Digested	Solid Bowl			24-30	90+	3-6		22
Primary - Digested	Solid Bowl			25-35	70-85	None		22
Primary - Digested	Solid Bowl			20-30	85-90		3-6	20
Primary - Digested	Solid Bowl		6	22-28	75-85		0	20
Primary - Digested	Solid Bowl		6	22-28	85		0.5-1	20
Primary - Digested	Solid Bowl			26-30	81-90	8		21
Primary - Digested	Solid Bowl			22-30	87-95	3-7		
Raw Primary + T.F.	Solid Bowl			24-30	90+	3-6		22
Raw Primary + T.F.	Solid Bowl			25-35	65-75	–		22
Raw Primary + T.F.	Solid Bowl	9.9-22	9.6	23	96-100	4-9		21
Raw Primary + T.F.	Solid Bowl			20-26	82-96	5-8		21
Raw Primary + T.F.	Solid Bowl			21-25	83-90	4-10		21
Raw Primary + T.F.	Solid Bowl			20-25	85-94	6-9		21
Digested Primary + T.F.	Solid Bowl		5.5	25+	40	None		23
Digested Primary + T.F.	Solid Bowl		5.6	20.2	90	6.74		23
Digested Primary + T.F.	Solid Bowl			20-28	90+	4-8		22
Digested Primary + T.F.	Solid Bowl			22-36	60-75	–		22
Digested Primary + T.F.	Solid Bowl			25	85		2.5-3.5	20
Digested Primary + T.F.	Solid Bowl			18-25	60-85	None		21
Digested Primary + T.F.	Solid Bowl			18-25	75+	8-16		21
Raw Primary + Waste Activated	Solid Bowl	40-80		18-20	40-60		None	20
Raw Primary + Waste Activated	Solid Bowl	40-80		10-20	85		4-5	20
Waste Activated (after roughing filter)	Disc	50-80	0.7	5-7	95-87	None		20
Waste Activated (after roughing filter)	Disc	60-270	0.7	6.1	97-80	None		20

LIQUID TO SOLIDS TRANSFER

I INTRODUCTION

A The transfer of dispersed contaminents in used waters from the soluble or suspended particulate form into a solids concentrate or sludge that is removable from the main body of water is a major operation of wastewater renovation or treatment.

B Larger suspended particulates of a density sufficiently different from that of water tend to separate readily by floatation, sedimentation, centrifugation, screening and allied unit operations.

1 Soluble materials in water may not be effectively separated by the operations listed in B although some concentration on preformed particulates generally occurs.

2 Small sized suspended particulates of the colloidal size range also tend to remain dispersed for a substantial time interval unless their characteristics are altered to promote agglomeration into separable clusters.

C Conventional treatment of wastewaters include many mechanisms favoring the transfer of soluble or colloidal materials into a solids concentrate or sludge. The nature and rate of transfer varies with the component to be separated, its biological, chemical, and physical characteristics and conditions of the system at the time.

D Mechanisms favoring component concentration include:

1 Assimilation and conversion to cell mass.
2 Storage on or in cell mass.
3 Sorption on cell mass or other surfaces.
4 Mechanical entrapment within the sludge mass.
5 Filtration effects.
6 Bonding due to ion-exchange properties of the sludge and substrate.
7 Coagulation due to reactions among water and/or sludge components.
8 Clumping effects as a result of naturally formed polyelectrolytes in the system.
9 Surface interaction or contact effects of mixing.

E This outline considers the factors favoring transfer from the dispersed phase to the sludge concentrate that occur within 1 to 20 minutes of contact. Chemical addition for coagulation is not considered part of this topic.

II CHARACTERISTICS OF BOD REMOVAL IN CONVENTIONAL TREATMENT

A A very high rate of BOD removal was observed in the first few minutes of contact of wastewater and activated sludge (1). The removal exceeding growth rate of the sludge was considered as biosorption.

B The British classified BOD removal under 3 main headings (2)

a High initial removal and storage
b Removal of substrate in proportion to cell growth
c Endogenuous oxidation of cell mass.

It was observed that there was a progressive loss in clarifying power of the sludge after repeated feeding at 1/2 hour intervals. Feeding at 2 hour intervals of aeration maintained clarifying power. Excessive aeration time between feeding tended to cause some loss in clarifying power.

C Velz (3), and Stack (4) attributed most of the BOD removal in trickling filters to the short term removal with later stabilization of the retained materials in the attached slimes.

D Ullrich and Smith (5) upgraded an overloaded activated sludge plant by splitting the aeration facilities into biosorption and sludge stabilization compartments with the clarifier following the biosorption compartment. The net gain by removing the overflow and stabilizing more concentrated sludge permitted about two times the solids stabilization time in the same tankage.

E In general, there can be no BOD removal in biological processes without sludge growth. Short time removal is attributed to some form of storage where sludge accumulation exceeds the rate of conversion into cell mass. Subsequent contact of waste material before growth has resulted in formation of new active surface (or overgrowth of a lacy mass of active organisms) results in decreased removal. Sludge residence time for conventional activated sludge is sufficient for oxidation of a significant fraction of the previously grown cell mass.

F The contact stabilization, biosorption, step feed and other processes involving a contact of wastewater and sludge for 1/2 to 1 hour followed by clarification and reaeration of the concentrated sludge has become popular. Contact processes have many advantages:

1 Cost of aeration tankage may be reducted materially in a contact process because the bulk of the liquid is released after a relatively short contact period.

2 Aeration cost is likely to be reduced because the high respiratory activity of the contact zone is maintained by higher solids concentration in the regeneration zone. The greater driving force throughout aeration should favor greater oxygen transfer per unit air input or per HP/hr.

3 Separation of contact and sludge reaeration tankage makes it unlikely that a short term toxic inflow will poison all of the process sludge. The reservoir of side stream sludge may be used to reestablish good performance earlier.

4 The reservoir of regenerated sludge in a side stream makes it possible to closely match sludge return with process demand. More sludge may be returned as the load rises with the drawdown replaced after about one displacement of the contact and clarifier units. Side stream equilization decreases probabilities of returning an understabilized sludge to process after several hours of high loading.

G Contact processes also have certain limitations that may result in a lowered treatment efficiency.

1 Certain substances, such as soluble materials, may or may not be removed in the sludge to a degree sufficient for the requirements. Substances such as phenol and sugar are rapidly assimilated but they must be assimilated to be removed as sludge. Unassimilated residuals during the permitted contact time pass into the effluent.

2 The contact stage may favor higher concentrations of inflow components or more rapid changes than the sludge can accommodate in the adjustment time provided. The net result is a lower degree of overall removal.

3 If oxygen demand in the contact stage exceeds oxygen supply, the absence of DO produces a less effective treatment. Both solids capture and sludge stabilization capabilities are reduced by a DO deficiency; concurrently, more oxygen is needed to restore sludge capabilities for purification.

4 A contact treatment process may be selective in removal of specific fractions of the load because some materials rare removed more effectively than others. For example, linear alkolate sulfonate (LAS) was observed to have about 75% transfer to the sludge. More efficient removal generally is sought.

5 It may be expected that a contact stabilization process will not provide as much cleanup as a conventional or complete mix activated sludge given the same load and conditions.

III TESTING FOR CONTACT PROCESS FEASIBILITY

A A basic requirement for any treatability study should include observations of contact kinetics. The removal versus contact time and conditions for general and specific cleanup is important.

B The test may be performed in many different ways. The essentials include:

1 Completely mix a definite volume of influent of known concentration with a definite volume of sludge solids of known concentration. Do not try to homogenize the mixture.

2 At preselected intervals, i.e., 5, 15, 30 minutes and 1, 2, and 3 hours withdraw a portion of liquid from the agitated and aerated mixture.

3 Separate the withdrawn mixed sample of liquid and solids rapidly. Centrifugation is recommended. Settling or filtration is too slow. Do not use coagulants unless these are to be used in the intended operation.

4 Test the liquid fraction and compare with the influent characteristics and with a reference sample of sludge and tap water in the same proportions and sequence. The tap water is used to check sludge washout upon dilution. This may be very high on an unstabilized sludge.

5 Tests used on the clarified fraction depend upon treatment objectives and the particular substrate and situation. Both general and specific tests are advisable.

a BOD is usually advisable. Remember that the ultimate BOD is more important than any one point on a progression.

b COD usually is applicable to estimate first stage oxygen demand.

c Total Kjeldahl nitrogen (TKN) is important for second stage oxygen demand estimates (TKNx4.57).

d Total organic carbon (TOC) and total oxygen demand (TOD) from carbon hydrogen nitrogen and sulfur demand are quick and valid if instrumentation and capable personnel are available.

e Turbidity, clarity and/or suspended solids (SS) are important because effluent quality usually depends upon the discharged solids.

f More specific tests, such as ammonia phosphorus, surfactants, phenolics, sugars, cyanides, or other components are important in proportion to their significance in the influent and the situation.

g Sensory observations regarding visual appearance (scum, oily residues, particulates, color, emulsions) odor, taste, or anything else observed that may provide a cue to subsequent quality are important.

h It is important to check removal selectivity. Commonly particulate materials are removed more completely than soluble materials. There is a large variation in removability of different substrates depending upon chemical, physical, and biological characteristics.

IV INTERPRETATION OF RESULTS::

A The bench test provides information useful for design selection of process and identification of likely problems during later operation.

1 Information derived from it is no better than the efforts and capabilities put into it.

2 The test should be carefully designed in line with the situation, information needed, and requirements to be met.

3 Bench data are unlikely to be precisely transferable to full scale operation. The principles are transferable. It is important to test known situations on bench and full scale to provide cues on what is or is not transferable for unknown situations.

4 It frequently is necessary to test intermediate scale operations to evaluate effects of scale-up when the bench work indicates a problem that cannot be evaluated effectively in bench scale operations.

B Certain observations may be encountered in bench work on transfer kinetics that have a real effect upon subsequent choice.

1 Adaptation of the active sludge for a particular influent is important. Transfer of substrate to the solids concentrate may improve as the sludge organisms adapt to assimilation and retention of the substrate. It is not essential that the substrate be completely degraded within contact time. As long as it has been modified enough to hold it in or on the cell mass, or sludge, as a storage product, it may be removed in process. Phenolics in acceptable concentrations are removed effectively by trickling filtration and other short contact operations by adapted organisms.

2 Concentration of substrates during contact is very important. A given concentration of phenolics may be removed effectively upon short term contact with an adapted sludge. Double or trebled concentration of the same phenolics under similar operating routine may result in high concentrations in the effluent and possibly a damaged sludge.

3 Combinations of substrates may show results that are materially different from either one separately. A sludge capable of accepting 100 mg/liter of mineral oil emulsion and of phenol separately without significant damage and good transfer kinetics failed completely upon exposure to simultaneous application. The combination resulted in cell mass disruption with the production of a centrate having a milky physical form, a strong phenol odor and a COD much greater than that of the combined influent.

4 Accumulation of a given influent substrate having a low oxidation rate in the sludge may result in retrogression of transfer kinetics upon repeated application. A single application of mineral oil at 100 mg/liter is likely to be transferred effectively to the sludge mass with moderate effects upon performance. The same dose or smaller doses on reapplication may result in little transfer of oil when the sludge attains an oil concentration (dry basis) of about 5 to 10%. The mineral oil degredation rate in an aerobic system usually is sufficient to maintain activity if the influent concentration of oil generally is less than 10 mg/liter. More than this on a continuous loading basis may result in sludge performance losses.

5 Activity of the sludge as indicated by performance or respiratory oxygen use is fundamental. An overloaded or poorly regenerated sludge cannot perform as intended, either for contact or conventional operation.

6 A mixture of substrates may show large differences in removal kinetics depending upon individual characteristics. LAS showed about 75% transfer to solids upon initial contact, whereas other wastewater constituents were about 90% removed in less than 10 minutes contact. It required 3 to 5

hours aeration for LAS concentration in the liquid phase to be reduced from 3 to 1 mg/liter.

V SUMMARY AND CONCLUSIONS

A It is not advisable to assume that contact stabilization on other short contact processes will be suitable unless tests or operational history on similar wastes show that required specifications are likely to be met.

B It may be expected that longer aeration periods in mixed influent and sludge will provide better cleanup of influent contaminents than a contact process under similar conditions and loading. Effluents may be upgraded by longer contact time, recycle, two stage operation or better operational control.

C Higher solids in relation to loading tend to increase removal and favor stabilization if DO can be maintained. Higher solids are likely to function as a trade-off for reduced time within certain limitations.

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SECTION IV MISCELLANEOUS UNIT OPERATION OR PROCESSES

	Outline Number
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STATUS OF CHEMICAL OXIDATION IN WASTEWATER TREATMENT

I Oxidation is a spontaneous and continuous process in nature. It occurs as slowly as in the natural purification (oxidation) process in a river, or as rapidly as in spontaneous combustion. Just as activated sludge waste treatment is a man-made acceleration of a natural biological purification process, chemical oxidation in waste treatment is a man-made acceleration of oxidation in nature. Physical and biological waste treatment processes have an upper limit for the removal of undesirable constituents from wastewaters. Beyond that point, no further reductions are realized unless process variables are strained to the point where the treatment method is no longer practical nor feasible.

II Any chemical change in which an element becomes more electropositive is oxidation. A species loses electrons upon being oxidized. Conversely, the oxidizing agent (oxidant) gains electrons and is reduced. The oxidation of organic compounds may be considered as the process of covalent bond fission in which one or both of the electrons of the disrupted bond are transferred or partially transferred to the oxidant.

A Homolytic oxidations are those reactions in which only one of the electrons of the disrupted covalent bond is transferred to the oxidizing agent.

B Heterolytic oxidations are those reactions in which both of the electrons of the disrupted covalent bond are transferred to the oxidizing agent.

C Halo-oxidants

1 Halogen compounds

2 Chlorine free-radical

D Oxy acids

1 Permanganate

2 Ferrate

TABLE 1: POTENTIAL OXIDATION SYSTEMS

System	Oxidant	Source
Environmental oxygen	O_2	liquid or gaseous oxygen
	O_2 + catalyst	$O_2 + MnO_2$
		O_2 + ultra-sound
Active oxygen	OH^*	Fentons reagent
	O_3	ozonator, corona
	O	ozone photolysis
Halo-oxidants	Cl_2	Cl_2
	$HOCl(OCl^-)$	hypochlorite
	Cl^*	chlorine photolysis
Oxy acids	MnO_4^-	$KMnO_4$
	$FeO_4^=$	Na_2FeO_4

III Effective oxidation presupposes that the oxidant has been selected with respect to the type of contaminant to be controlled and applied under conditions favoring its effectiveness. Condition variables include:

A The pH of the oxidation system may greatly influence behavior.

1 Chlorine application in a surface water reacts to form HCl + HOCl. Reaction of HOCl with oxidizable materials forms more HCl. If alkalinity is insufficient to neutralize the accumulated acid the pH may be reduced to the point where ammonia or cyanide cannot be destroyed by chlorination.

2 Permanganate oxidation of organic amines to form ammonia and CO_2 is effective over a wide range in pH. Dichromate appears more effective in highly acid media.

B Temperature has a large effect upon reaction rate and may alter the nature of the oxidizing agent or its availability in the aqueous system.

1 Chlorine, ozone, H_2O_2, react very slowly near freezing temperatures. Near the boiling point, the oxidant may be driven from the system or decomposed in undesirable side reactions.

2 Oxy acids are much more effective and show higher oxidative efficiencies at elevated temperatures.

C Oxidative energy may be favored by appropriate catalysts.

1 Permanganate oxidation at ambient temperatures is favored by the presence of ferrous or ferric iron.

2 The presence of ionic silver favors oxidation by dichromate.

D Adequate mixing of oxidant and aqueous media affect both oxidation efficiency and nature of the process.

1 Chlorine application necessitates vigorous mixing to dilute the chlorine gas to a point where it will not be lost in gaseous form and to prevent undesirable side reactions due to a tremendous excess of chlorine at local sites.

2 H_2O_2, ozone, and hydroxyl free-radicals are notoriously unstable. They generally are applied in relatively low concentrations or formed in situ, to favor contact with undesired contaminants prior to uncontrolled side reactions.

E Time is essential to permit desired oxidations to be completed. Time requirements vary with the particular oxidant and the nature of the substances to be treated.

1 Chlorination of a relatively stable water may favor formation of free available residual chlorine favoring high germicidal effectiveness in a short interval of time. Grossly contaminated water chlorination favors production of combined available chlorine which is likely to require a much larger application dosage and more time for disinfection.

2 Permanganate oxidation is characterized by a latent period followed by an auto catalytic effect once oxidation has started. Catalysis reduces this effect but does not eliminate it.

F The concentration of contaminants controls the type of oxidant feasible for economic use and the sequence in which a combination of oxidants may be applied.

1 The concentration of combustible organic materials determines whether high temperature incineration is feasible or not. Heat recovery during oxidation vs heat requirements for drying are major criteria.

2 Economics of the over-all system largely determine which oxidants will be employed for each situation.

a Phenol may be oxidized by chlorine, ozone, and chlorine dioxide. Large scale continuous operations commonly employ biochemical stabilization because capital and operational costs of aeration are likely to be lower than for chemical oxidation.

b Conversely, oxidation may be more economical for discontinuous or low concentrations of phenol.

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PRACTICAL ASPECTS OF OXYGEN TRANSFER

I INTRODUCTION

A The Need

An adequate supply of dissolved oxygen, which is normally transferred by mechanical means, is required by aerobic biological oxidation process such as activated sludge and aerated lagoons.

B Transfer Techniques

Many different oxygen transfer devices are marketed. All of them transfer oxygen from air by the generation of air-water interfaces.

The potential use of a pure oxygen atmosphere and the generation of oxygen-water interfaces may be implemented in the future to meet higher rates of oxygen demand.

C Objective

The objective in any oxygen transfer system is to adequately provide the oxygen requirements and to do so as economically as is possible.

II OXYGEN TRANSFER THEORY

A Oxygen transfer across an air-water interface follows a first order relationship which can be expressed as:

$$N = K_L (C_s - C_L)$$

which is based on the two film theory and the assumption that most of the resistance is on the liquid side. N is the mass transferred per unit of area per unit of time or the rate of diffusion. K_L is the overall liquid mass transfer coefficient, C_s is the oxygen concentration at the interface and C_L is oxygen concentration in the body of the liquid.

B The area through which mass transfer is taking place usually is not known; hence, area is combined with the mass transfer coefficient to give a composite coefficient K_La

$$N_a = K_La (C_s - C_L)$$

where N_a is mass transferred per unit of time per unit of driving force.

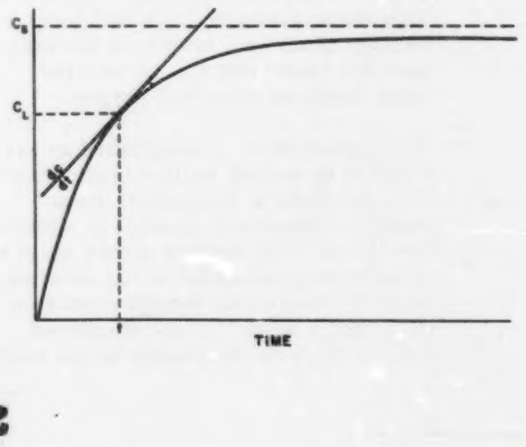
C Considering oxygen transfer into a given body of water as a special case, mass transfer can be expressed as:

$$\frac{dC}{dt} = K_La \; (C_s - C_L)$$

The value of K_La in concentration terms applies only to the particular aeration system in which the measurements are made. The relationship is shown graphically in Figure 1.

Figure 1

OXYGEN TRANSFER RELATIONSHIP
CONCENTRATION BASIS



III MEASUREMENTS OF OXYGEN TRANSFER

A Non-Steady State Systems

Interpretation of oxygen transfer into water where oxygen consumption is not involved utilizes the integrated form of the differential equation for the calculation of the oxygen transfer coefficient

$$K_La = \frac{\ln \dfrac{C_S - C_{L_1}}{C_S - C_{L_2}}}{t_2 - t_1}$$

Practical evaluation of non-steady state oxygen transfer must recognize the following factors.

1 Determinations of oxygen concentration are usually accomplished by the Winkler titration procedure or with dissolved oxygen probes. Dissolved oxygen probes are convenient and suitably accurate, but the response time of probes is significant and must be accounted for in the interpretation of results.

If samples can be collected rapidly enough (such as by the use of pumps), the problem of response is minimized by utilizing the Winkler determination. There are interferences with the Winkler such as high results due to cobaltous ion concentrations (used as catalyst) of greater than about 0.1 mg/l. Also, in high shear systems, colloidal dispersion of air (not visible to the naked eye) can occur and will be titrated incorrectly as dissolved oxygen.

2 Deoxygenation is accomplished by the addition of sodium sulfite which reacts with the dissolved oxygen to form sulfate. Cobaltous chloride is added as a catalyst. The sodium sulfite must be in solution when added to the aeration basin to insure that the apparent rate of oxygen transfer is not interfered with by the rate of solution of the sulfite. The cobaltous ion must be added in catalytic concentrations. If water in the system contains materials which complex cobaltous ions, enough cobaltous chloride must be added to satisfy the complexation reaction and to provide a catalytic concentration. The cobaltous ion may interfere with the determination of oxygen by the Winkler procedure, but it does not interfere with dissolved oxygen probes.

3 In very large aeration basins, dispersion of the sodium sulfite throughout the basin is a problem. Care must be taken to achieve thorough dispersion. Usually, introduction of the sulfite solution into the suction flow to the aeration equipment is adequate.

4 Non-steady state transfer becomes very difficult when more than one entrainment aerator exists in a basin because of the problem of uniform dispersion.

5 The proper concentration of dissolved oxygen at saturation must be used. If air-water interfaces are generated under a head of water, the dissolved oxygen concentration at the mean pressure should be utilized. When entrainment aerators are involved, saturation values at atmospheric pressure are usually adequate. However, in smaller basins, bubbles may be mixed into the basin volume rather than escaping at the surface. Under this condition, the mean saturation value is determined by observations of the actual saturation value in the basin.

Non-steady state data from a small-scaled pilot plant used to evaluate the aerated lagoon process are shown in Figure 2. Tap water was introduced into the aeration basin and oxygen transfer data were collected. The basin was then filled with treated wastewater and oxygen transfer data were collected under identical conditions. The result showed that the same transfer effort resulted in a transfer rate to the wastewater equal to 59 percent of the rate to tap water.

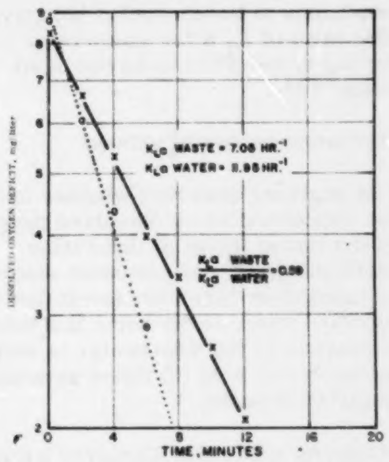


Figure 2

OXYGEN TRANSFER COMPARATIVE K_La

B Steady State Systems

For any system under aeration, the instantaneous rate of oxygen transfer is directly proportional to the driving force $C_S - C_L$. Therefore, if an aeration effort is applied to a system which has a demand for oxygen, an equilibrium is established when the driving force is reduced to a point where the rates of oxygen transfer and oxygen demand are equal.

$$\frac{dc}{dt} = K_La\,(C_S - C_L) = r$$

where r is the rate of oxygen consumption. Data determined at equilibrium may be utilized to determine the coefficient of oxygen transfer.

$$K_La = \frac{r}{C_S - C_L}$$

The steady state technique must be utilized for the examination of oxygen transfer into the activated sludge process because of the following reasons.

1 Raw wastewater, which might be used in non-steady state evaluation, may contain surface active agents which will be degraded in the biological system. In other cases, surface active agents may be synthesized during biological degradation. Therefore, the raw wastewater cannot be assumed to be a representative of water in the mixed liquor.

2 The treated effluent is not a representative system because it does not contain the activated sludge solids.

3 The actual mixed liquor is the representative system because it contains the factors of suspended solids and surface active materials in the proper concentrations. Additionally, carbon dioxide evolution from the system is in progress. Carbon dioxide evolution in highly active systems can reduce the rate of oxygen transfer by as much as 25 percent and, therefore, is a significant factor.

Oxygen transfer evaluation under steady state conditions should consider the following factors.

1 Oxygen uptake rate in the mixed liquor is established through a dynamic ratio of food-to-microorganisms. If a mixed liquor sample is removed from the system, the food supply is shut off, and the oxygen uptake rate may decrease significantly within a matter of seconds.

In small systems, oxygen uptake rate should be determined by stopping aeration, continuing feeding, and providing gentle agitation to suspend the activated sludge solids while the rate of decrease in dissolved oxygen is observed.

In large systems, the mixed liquor should be pumped through a container which contains a dissolved oxygen probe (Figure 3) until an essentially constant dissolved oxygen concentration is observed. The pump is then stopped and oxygen uptake rate is observed immediately thereafter. The solids must not be permitted to settle or additional air input supplied during test.

2 In large aeration basins, the value of C_L cannot be the same at all locations and must decrease from the time that mixed liquor leaves the aeration zone until it returns. The mean value of C_L should be determined.

3 Dissolved oxygen values at saturation involve the same problems as those which were noted for non-steady state oxygen transfer evaluation. The same considerations must be applied.

IV FUNDAMENTAL DATA IN OXYGEN TRANSFER SPECIFICATIONS

Based on the preceding discussion, it is relatively apparent that a manufacturer cannot provide oxygen transfer equipment on the basis of a stated dissolved oxygen requirement. It is necessary to provide him with additional information about oxygen transfer resistances, saturation values, minimum allowable concentration of dissolved oxygen and range of operating temperatures.

1 Oxygen transfer resistances (α value)

Information about resistances to oxygen transfer are obtained by the engineer by determining $K_L a$ values for the activated sludge system (steady state data) and tap water (non-steady state data) under identical conditions in bench-scaled equipment. The ratio of $K_L a$ for wastewater to $K_L a$ for tap is referred to as the alpha value (α).

2 Saturation values (β values)

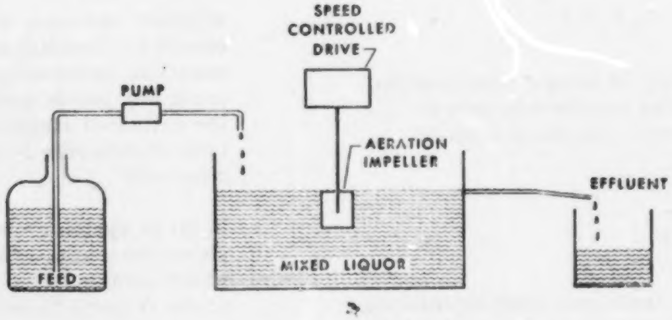
The engineer observes whether or not the concentration of dissolved oxygen in the mixed liquor at saturation (determined on a supernatant sample) is equal to or less than saturation in distilled water at the same temperature. Saturation in the wastewater is defined as the factor beta (β) times saturation in distilled water.

3 Minimum allowable dissolved oxygen concentration

The mixed liquor of the activated sludge process must remain aerobic, but the dissolved oxygen concentration in the

Figure 3

OXYGEN TRANSFER DETERMINATION
BENCH-SCALED APPARATUS FOR STEADY-STATE DATA



$$K_L a = \frac{r}{C_S - C_L}$$

process should be allowed to go as low as possible to take advantage of the maximum driving force. The minimum allowable dissolved oxygen concentration is usually about 0.5 mg/l, but in certain cases higher values may be required.

4 Range of operating temperatures

As the operating temperature increases the driving force decreases because of the decreased solubility of dissolved oxygen. Normally, the limiting oxygen transfer conditions are found at elevated temperatures.

If very cold operating conditions are anticipated (in the order of zero to 5° C) limiting oxygen transfer can be encountered because the oxygen transfer coefficient varies as a function of temperature.

$$K_L a_T = K_L a_{20} \cdot 1.024^{20-T}$$

5 Summary of fundamental oxygen transfer data

a Oxygen transfer requirement

b α value

c β value

d Minimum allowable dissolved oxygen concentration

e Range of operating temperatures

6 Additional considerations should take into account basin configuration and the numbers of aeration units as related to adequate mixing of basin contents as well as dispersion of dissolved oxygen.

In large systems where the demand for oxygen is variable, economy through power savings can be realized if the oxygen transfer capacity is paced in proportion to the oxygen demand. Dissolved oxygen analyzers, logic units and interfacing equipment are used to control the oxygen transfer equipment.

This outline was prepared by Vernon T. Stack, Director of Research and Development, Weston and Stack, Inc., Newtown Square, Pennsylvania.

OXYGEN TRANSFER DURING DIFFUSED AIR OPERATIONS

I STACK CONSIDERED NON-STEADY STATE AND STEADY STATE OXYGEN TRANSFER ESTIMATES FOR DESIGN PURPOSES.

These methods are not attractive for evaluation of oxygen transfer estimates for diffused aeration systems under continuous treatment conditions. This discussion includes techniques used at Milwaukee (1) for guidance during oxygenation upgrading of plant units.

II MILWAUKEE EXPERIENCE

A Test basins were operated with the usual content of wastewater and activated sludge flows.

B The material balance of oxygen through the system gas phase was used as described (2).

1 Samples of escaping gas were collected at predetermined points along the width and length of the aeration basins and analyzed for CO_2, O_2 and N_2.

2 Gas escape rates were measured at these points and compared with metered air input on the basis of N_2 content of the gas phase.

3 Oxygen dissolved was determined on the basis of these values, i.e.

$(W_{air}$ in $^{X}\%$ 0_2 in$)$-W_{air} out $^{X}\%$ 0_2 out$)$ = 0_2 trãnsferred to the liquid phase.

C The oxygen transfer rate (lbs/day)

$$= K_{La} \cdot V (C_s^{1} - C_L) \quad \text{where}$$

K_{La} = the 0_2 rate coefficient (day^{-1})

V = basin volume corrected to consistent units

C_s^{1} = saturation value of 0_2 corrected for diffusor submergence depth

C_L = body liquid mg DO/liter

D As used the O_2 transfer rate (lbs/day)

$$= \frac{A\,[(WC_{O_2\,in}) - (WC_{O_2\,out})] \times W_{air}}{\Sigma\ W_{air}}$$

where:

W = weight rate of gas or air in lbs/day/sq ft

C = Concentration of oxygen in lbO_2/lb_{air}

A = Surface area of the aeration basin (sq ft)

1 A weighted average was used for each of the basin sampling points to estimate results for the entire basin.

2 Gas escape rates were corrected for changes in passage and compared with meter readings. Gross differences were attributed to inadequate sampling. The sampling program was considered satisfactory when agreement was within + or -25%.

E The % Oxygen transfer efficiency

$$= (W_{air}\ \text{in} \times Wf\ O_{2\ in}) - (W_{air}\ \text{out} \times Wf\ O_{2\ out}) \times 100$$

Wf = wt. fraction O_2

1 The mean efficiency ranged from 3.9 to 6.5% oxygen transfer before modification.

2 Mean efficiency ranged from 9.6 to 17.1% in the modified system.

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This outline was prepared by F. J. Ludzack, Chemist, National Training Center, DTTB, MDS, OWP, EPA, Cincinnati, OH 45268.

REMOVAL OF AMMONIA FROM WASTEWATER

I INTRODUCTION

A Stripping of gases from liquid streams is a common occurrence in the chemical processing industry. Past applications in the wastewater field have largely been incidental. An important application appearing on the horizon is the stripping of ammonia from wastewaters which are excessively rich in this nutrient.

B Stripping of a gas from a liquid by an inert gas and absorption of a gas from a mixture of gases by contact with a liquid are an important chemical engineering unit operations. The basic principles and design methods are presented in many standard chemical engineering texts (1, 2, 3). These methods depend on a knowledge of gas-liquid equilibria, mass transfer relationships, and material balances applied to the contacting device employed.

II CONTACT DEVICES

Intimate contact of gas and liquid may be achieved in many ways. For example, two well known methods of oxygenation include introducing air in the form of fine bubbles into the liquid such as in activated sludge mixed liquor, and spraying liquid into the air as in certain water treatment operations.

A When the absorption or stripping of a gas must be nearly complete, the most effective means for carrying out the operation is by countercurrent contact. A good example of such a device is the ordinary water-cooling tower. Warm water entering the top of a tower flows downward across slats and contacts an upwardly flowing stream of air.

B The water-cooling tower is not as efficient a contacting device as a tower packed with Raschig rings or some other efficient packing material. However, the pressure drop required to move substantial quantities of air through a conventional cooling tower is very low. In applications such as the stripping of ammonia from water, large volumes of air are required. Power cost, which is proportional to the product of volumetric flow rate and pressure drop, is unreasonably high for this operation when ordinary packed towers are used. In order to keep power costs low, the cooling tower design has been adopted despite a lower contact efficiency.

III GAS-LIQUID EQUILIBRIUM

The equilibrium relationship between a liquid and a soluble gas carried by an inert gas can be expressed by Henry's law:

$$P_a = H C_a \qquad \text{Equation 1}$$

where P_a = partial pressure of the soluble gas (e.g. mm Hg)

H = Henry's Law constant

C_a = concentration of the soluble gas in the liquid (e.g. g/ml)

A Henry's Law is generally satisfactory for low concentrations. The condition is generally met by the concentrations encountered in wastewaters.

B For water solutions where the dissolved gas can ionize, the situation becomes quite complex. The equilibrium relationship then becomes a function of pH. Moelwyn-Hughes (4) considers this problem. For the case of ammonia in wastewater, stripping only becomes practical when the pH is increased to about 11 and the ammonia is completely in its molecular form.

1 Data collated by Farrell, Stern, and Dean (5) indicate the following values of the Henry's Law constant for ammonia in air at 1.0 atmosphere pressure:

Temp. (° C)	k
10	0.42
20	0.70
30	1.15
40	1.8

where $k = y/x$ Equation 2

x = mol fraction of ammonia in water

y = mol fraction of ammonia in air

The Henry's Law constant is given in terms of mol fractions in this table because mol fractions are more useful in material balance calculations than the units used in Equation 1. The value of k is dependent on total pressure, whereas the value of H (Equation 1) is independent of total pressure. This is not an important drawback since ammonia stripping is done at atmospheric pressure.

2 Material balance

The quantity of air that must be used to strip ammonia from water is of great importance. Experimental studies (6) have indicated that 400 cu. ft. of air per gal. of wastewater is required to remove 90 percent of the ammonia from wastewater, using a water-cooling tower. The reasonableness of this figure can be verified by calculating the minimum air-to-water ratio for a "very tall" tower. This calculation can be carried out by the use of the equilibrium data and a material balance around the countercurrent stripping tower.

a Figure 1 represents a typical countercurrent tower with inlet and outlet streams identified. A material balance over the entire tower may now be drawn on the basis of coding for Figure 1:

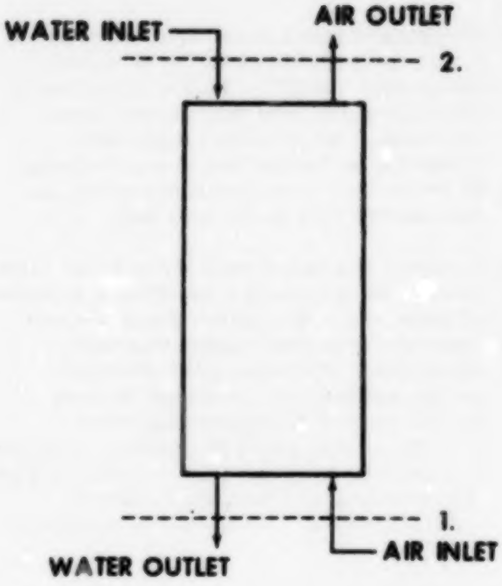
$$L(x_2 - x_1) = G(y_2 - y_1) \quad \text{Equation 3}$$

or

$$(y_2 - y_1)\frac{G}{L} = (x_2 - x_1) \quad \text{Equation 4}$$

GAS TRANSFER UNIT SCHEMATIC

FIGURE 1



Let x_2 = mol fraction ammonia in water, at water inlet

y_2 = mol fraction ammonia in air, at air outlet

x_1 = mol fraction ammonia in water, at water outlet

y_1 = mol fraction ammonia in air, at air inlet

Let L = mols water per hour

G = mols air per hour

b If it is desired to remove 90 percent of the ammonia from the water at 20º C and the inlet air contains no ammonia, the minimum air-to-water ratio (G/L) can be calculated with the aid of the equilibrium relationship. Both air and water are assumed to be at 20º C in this calculation, and the air is presumed to be saturated with water vapor. At the minimum G/L ratio, the air and water will be in equilibrium with each other at the top of the tower (position 2 in Figure 1). Substituting these values into Equation 2 and 4, we obtain:

From equation 2, $y_2 = 0.7 x_2$

From equation 4, $(y_2 - o) \left(\frac{G}{L}\right)_{min.} = (x_2 - 0.1 x_2)$

Solving these equations simultaneously, we obtain $(G/L)_{min.}$ equals 1.29 mols air per mol of water or 224 cu. ft. of air per gal. of water.

c The result of this calculation indicates that the experimentally determined value of 400 cu. ft. per minute as a practical operating quantity is reasonable.

IV TOWER VARIABLES

A Calculation (III. B) is an oversimplification of the real situation chiefly because we cannot stop the tower from acting as a water-cooling tower. If the air enters the tower unsaturated, it will cause the water to cool as a result of evaporation. Because of the large quantity of air relative to water (for a cooling tower), the water will cool very nearly to the wet-bulb temperature of the entering air. The equilibrium relationship will no longer be as simple as Equation 2. Nevertheless, the above calculation is useful in illustrating the principles involved.

B The size of the tower needed to strip ammonia from wastewater depends on the rate of mass transfer in the tower. It is beyond the scope of this lecture to discuss the mass transfer rate equations. It is sufficient to note that Slechta and Culp(6) achieved 90 percent removal in a cooling tower approximately 25 ft. in height at air-to-water ratios of about 400 cu. ft. per gal. of wastewater. Similar removals can be expected in a similarly constructed tower.

C Effect of Air Temperature

Slechta and Culp(6) noted that performance of their tower was much poorer in the winter. The reason for this becomes obvious when Henry's Law constants are examined. The constants drop rapidly with temperature, indicating the increased solubility of ammonia in water at lower temperatures. The cure for this reduced removal is not to increase tower height but to increase the air-to-water ratio.

The high air-to-water rates indicate that serious difficulties will be encountered at low temperatures and low humidities. If the wet-bulb temperature falls below 0º C, ice formation in the tower is to be expected. This will require a shutdown of the tower if damage is to be prevented.

D The full-scale tower at South Lake Tahoe (7.5 mgd capacity) will be of the cross-flow type. This will require a higher air-to-water ratio to remove an equivalent amount of ammonia, but the power cost may not increase substantially since pressure drop will be lower than for a countercurrent tower.

Cross-flow towers include the possibility of periodic reversal of flow without seriously affecting tower performance. This capability may reduce the freezing problem by flow reversal if freezing occurs at the air inlet section.

The full-scale ammonia stripping tower at South Lake Tahoe will be operational during the winter of 1968-69. Definitive operating date will be available shortly after that time.

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BASIC PRINCIPLES OF NEUTRALIZATION

I Acidity and Alkalinity are reciprocal terms. Substances yielding hydrogen ions upon hydrolysis are acids; those yielding hydroxyl ions upon hydrolysis are basic or alkaline. The reactions of acids and alkaline materials to form water and associated salts are considered neutralization (1).

A The pH of a media is an index of hydrogen ion activity and is used as an indication of acidity and alkalinity while not a measure of either.

B The "total" acidity or alkalinity often are used to estimate the buffer capacity (resistance to a change in pH) of a solution.

C Neutralization dynamics frequently involve "weak" acids or alkaline materials that are characterized by appreciable buffer capacity.

1 Strong acids, such as hydrochloric and sulfuric and strong alkalies such as sodium hydroxide are characterized by little buffering action and when neutralized have an equivalence point close to the thermodynamic neutral point of pure water at pH 7.0.

2 Weak acids such as phosphoric and acetic acids and weak bases such as ammonia or carbonates tend to have equivalence points during neutralization that may be located on the pH scale above or below pH 7.0 depending upon characteristics of hydrolyzable cations and anions of the salts produced by neutralization.

3 Acids or alkalies with more than one hydrolyzable hydrogen or hydroxyl ion will have one equivalence point for each of the cited ions produced in solution, i.e., H_2SO_4 will have 2, H_3PO_4 will have 3.

4 The titration curve of the volume and concentration of neutralizing agent versus pH in graphic form (considered later) provides a means of relating total acidity or alkalinity with pH, estimating the quantity of chemical required for sample neutralization, and of controlling the operation.

D Natural waters generally are buffered by CO_2, HCO_3^-, $CO_3^=$, and other ions within a pH range of 6.5 to 8.5. Certain organisms may function within a pH range of 2 to 10. Greater extremes have been reported but reduced organism activity are characteristic of systems near extreme ranges. It was recommended (1) that no highly dissociated materials should be added to surface waters in quantities sufficient to lower the pH below 6.0 or to raise the pH above 9.0.

E Neutralization commonly is performed to meet Water Quality Standards usually expressed in terms of pH. Economics and operational problems to meet objectives vary with the nature of the substance to be neutralized, chemicals selected for neutralization, nature and amount of solids produced, contact requirements, reaction rates, buffer capacity, process control and reuse requirements of the receiving water.

II Process water neutralization may be achieved by mixing acid or alkaline process waters, when available. It is more likely that mixed acid and alkaline wastewaters will show excess acid. Further, alkaline wastewaters are more amenable for treatment by chemical recovery processes. Therefore, acid wastewaters more commonly require neutralization by purchased alkaline agents.

A Alkaline substances commonly considered for neutralization include (2, 3):

1 Sodium hydroxide and sodium carbonate are convenient, controllable, and commonly available but expensive. They are generally used for small or occasional application or where limitation of sludge deposition is sought.

2 Lime is the most commonly and widely used alkaline agent because of availability, low cost, and high capacity. Sludge bulk after lime neutralization is a major problem but recovery is possible.

a Calcined lime (CaO) or slaked lime ($Ca(OH)_2$) may be purchased and used in slurry form.

b Limestone or dolomitic limestone are cheaper than (a) but are more difficult to use. Reaction rates and coating favor incomplete reactions. Physical form and mixing are critical in the use of lime or limestone. High calcium lime in finely divided state is generally preferred for neutralization.

c Combinations of chemicals may be used such as a roughing neutralization by contact with a bed of limestone, followed by adjustment of remaining acidity with high calcium lime.

d Rudolfs (3) cites a 20 fold cost differential per ton of basicity from low cost dolomitic lime to sodium hydroxide.

B Alkaline wastewaters less commonly require neutralization but are a problem for certain industries.

1 Sulfuric acid is the cheapest and most readily available neutralizing chemical.

2 Where available, CO_2 or SO_2 may be applied in gaseous form. Flue gases are accessible and economical for neutralization of alkaline waters in certain industries.

III Economics are the major neutralization problem but a large factor in economics is relatable to ionic equilibria and their effects upon the system.

A It is highly unlikely to produce one unit equivalent of neutralized product from one unit equivalent of purchased neutralizing chemical. Activity coefficients less than unity are associated with thermodynamic properties such as solubility, reaction rate, and distribution among possible ionic species; in addition, practical problems such as contamination, coating, competing reactions, contact or mixing, solids production drainability and disposability seriously affect activity and feasibility.

B The graphic representation of pH versus added titrant, the titration curve, provides a means to characterize the substance to be neutralized, the amount of neutralizing agent required, aids in selection of neutralizing agents in line with cost or feasibility and assists process control in terms of a pH index. A titration curve may be used differently for classification or process control in a particular situation.

1 Titration curves for classification purposes commonly employ a standard acid or alkali titration.

2 Titration curves for process optimization commonly are based on chemicals likely to be used in process in a manner designed to indicate process variables such as contact, time, temperature, nature and amount of solids, and handling characteristics in relation to system pH.

3 The following titration curves illustrate terminology, characteristics, and changes with respect to different samples titrated with standard solutions (4, 5).

a Figure 1 illustrates titration of a strong base (NaOH), with a strong acid, (HCl). Early additions of the titrant have a minor effect upon pH because NaOH plus product NaCl has little buffer capacity. The curve is relatively flat for each addition of titrant prior to the inflection. The inflection indicates an approach to the equivalence point. Higher concentrations of sample components would move the flat portion of this curve toward the extremes. The equivalence point is graphically located half way along the straight line of the graphic between the upper and lower inflections.

Strong acid and base equivalence points commonly occur near pH 7.0. The product of volume and concentration of added titrant at the equivalence point is an estimate of sample basicity.

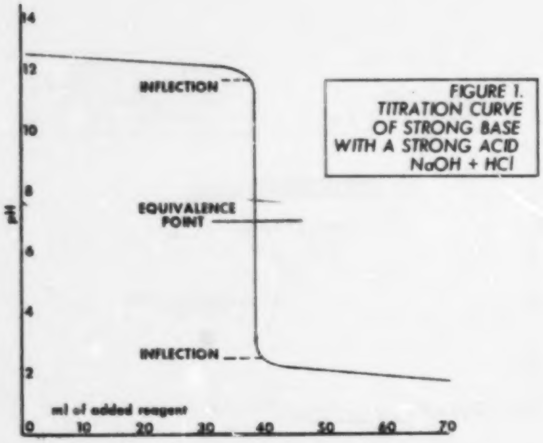

FIGURE 1. TITRATION CURVE OF STRONG BASE WITH A STRONG ACID NaOH + HCl

b The graphic (Figure 2) represents behavior of weak acetic acid titrated with a strong alkali, NaOH. Early additions are characterized by significant changes in slope of the curve as the pH of acetic acid shifts to one characterized by a buffer solution of acetic acid and sodium acetate. Higher concentrations would accentuate the earlier inflection and flatten the curve beyond the first inflection. The second inflection produced by subsequent titrant addition signals approaching equivalence, the third inflection indicates an excess of NaOH. Additional titrant exhibits less change in pH with subsequent additions as the strong alkali is controlling pH. The pH range between the second and third inflections includes the equivalence point. The straight portion between inflections is significantly shortened and shifted upward on the pH scale because the major component, sodium acetate, has a strong base cation and a weak acid anion. Concurrently, the equivalence point is in the alkaline pH range.

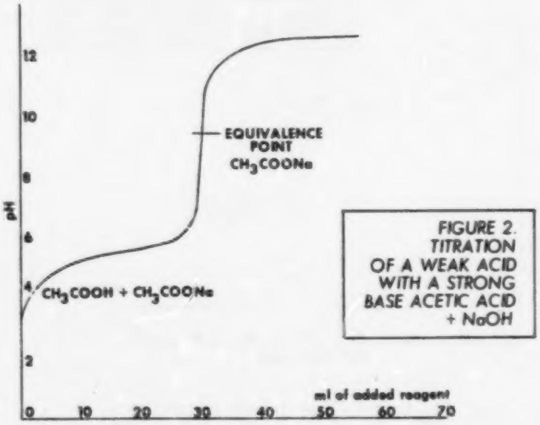

FIGURE 2. TITRATION OF A WEAK ACID WITH A STRONG BASE ACETIC ACID + NaOH

c Figure 3 indicates the opposite situation wherein a weak base is neutralized with a strong acid. The early inflection is in the high range of the pH scale as the pH control shifts from that of NH_4OH to a mixed NH_4OH and NH_4Cl buffered system. The second inflection point is lower on the pH scale with a range in pH on both sides of the equivalence point narrow in comparison to Figure 1. The equivalence point is in the acid range because the salt produced at the equivalence point consists of a weak base cation and a strong acid anion. The curve produced by added acid beyond equivalence is relatively flat because of excess strong acid.

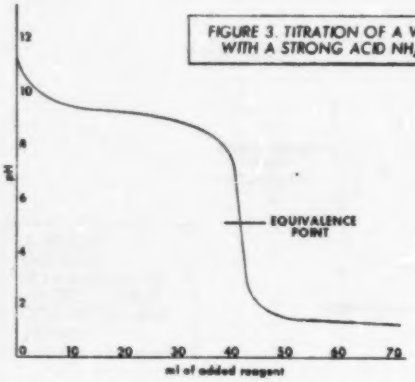

FIGURE 3. TITRATION OF A WEAK BASE WITH A STRONG ACID $NH_4OH + HCl$

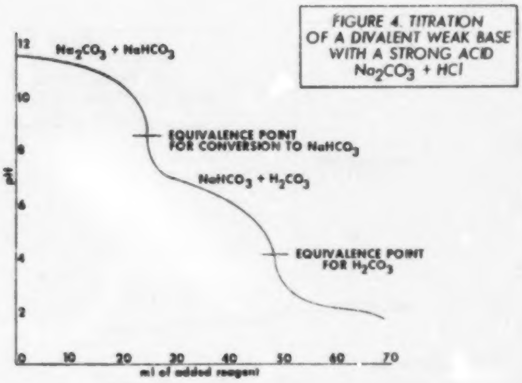

FIGURE 4. TITRATION OF A DIVALENT WEAK BASE WITH A STRONG ACID $Na_2CO_3 + HCl$

d Figure 4 illustrates titration of a relatively weak dibasic Na_2CO_3 with a strong acid (HCl). First addition of acid titrant converts the system from Na_2CO_3 to $Na_2CO_3 + NaHCO_3$. This phase is completed at the first equivalence point where $NaHCO_3$ becomes pH controlling. The area between the two equivalence points represents conversion of $NaHCO_3$ to H_2CO_3. Beyond the second equivalence point H_2CO_3, CO_2 and HCl are controlling. NaCl increases from left to right but has little effect upon pH. One equivalence point is located in the alkaline, another in the acid pH range. The complex buffer system contributes to high slopes between less definite equivalence points.

e Figure 5 presents a much more complex situation where the neutralized substance includes dibasic sulfuric acid and 2 valence states for iron. Inflection points are confusing and would be more complex if dibasic calcium oxide had been used as the titrant instead of NaOH. The inflections mainly represent ionics of reduced and oxidized iron species.

f Titration curves for mixed ionic species such as wastewaters often present successive and uninterpretable inflection points. Titration curves on separate components may be necessary to relate behavior on a pH scale for guidance in control of the mixed system. A separate presentation considers practical aspects and problems in neutralization of complex ionic systems.

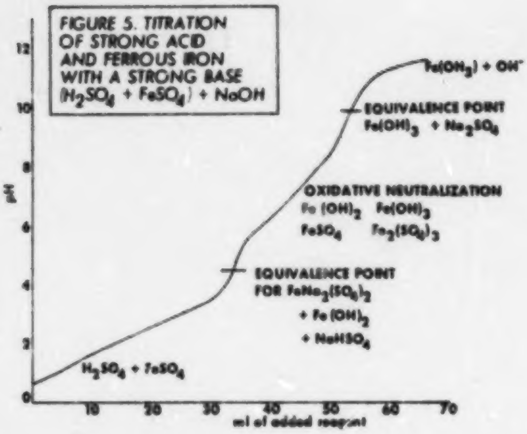
FIGURE 5. TITRATION OF STRONG ACID AND FERROUS IRON WITH A STRONG BASE (H_2SO_4 + $FeSO_4$) + NaOH

ACKNOWLEDGEMENT

This outline includes materials made available by R. C. Kroner and J. W. Mandia.

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PRACTICES AND PROBLEMS IN THE NEUTRALIZATION OF STEEL PICKLING WASTES

I INTRODUCTION

Steel Pickling Wastes is a broad term used to cover the problems faced by the steel industry today in disposing of all the wastes from the pickling operations. For many years, the term "Waste Pickle Liquors" was used. This covered only the spent pickling solutions from the picklers, and these were predominately sulfuric acid liquors.

By far the greatest volume of pickling wastes come from the continuous pickling process. In this process the steel strip is passed through four or five large pickling baths for the removal of the iron oxides. The strip is then rinsed with large quantities of water to remove the last traces of the pickling solution. The spent pickling solutions contain 6-10% acid and 18-20% iron salts. The rinse waters have a very low acid and iron content.

II The pickling wastes requiring treatment as well as the method used for treatment will vary from plant to plant.

A As far as neutralization is concerned, the treatment of the following wastes must be considered:

1 Spent pickling solutions only may include:

- a Sulfuric acid solutions
- b Hydrochloric acid solutions
- c Nitric acid solutions
- d Hydrofluoric acid solutions
- e Nitric-hydrofluoric acid solutions

2 Rinse waters will contain the acids listed above.

3 Combination of spent pickling solutions and rinse waters.

B Neutralization of spent pickling solutions has not been generally accepted by the industry because of the very high cost involved and the tremendous sludge disposal problem which is created. These facts will be brought out in discussing the several neutralization units in operation in Armco. The DuPont process is being advanced to reduce the sludge disposal problem but only two or three very small units are in operation.

III I would like to review with you several neutralization installations being operated by Armco.

A Butler Works Neutralization Facility No. 1 Plant

1 The neutralization of the combined spent pickling solutions and all rinse waters is not new to the Butler organization, as these wastes have been treated in much the same manner for forty years.

a Complete treatment is required in this case because the Butler Plant is located on Connoquenessing Creek, which is used as a recreational area below the plant. In addition, the flow in the Creek during the dry summer months is less than 5 m.g.d. for extended periods.

b Many and varied ideas have been tried to treat waste pickle liquor either separately or with rinse waters without success.

c To further complicate the problem, stainless and electric grade steels are processed at this plant so that considerable nitric and hydrofluoric acid is used. No attempt is made to segregate these wastes.

2 All spent pickling solutions and rinse waters from all units in the plant flow to two large collecting sumps. These sumps are concrete, acid brick-lined 23 ft. inside dia. and 18 ft. deep - combined operating capacity 50,000 gal. These sumps serve to even out the concentration of liquor, temperature, and flow going to the treatment plant.

3 From the sumps the wastes are pumped to the first of four 18 ft. dia., 10 ft. deep redwood tanks, 17,000 gal. capacity each. These tanks are set one slightly higher than the other so that the liquor flows by gravity through the system. Each tank has an overflow box running to within 2 feet of the bottom so the flow is from the bottom of each tank to the top of the next tank in series. Each tank is also equipped with a 1,700 gpm recirculating pump which draws the wastes from a center bottom outlet and recirculates them to the top.

4 One additional redwood tank is provided to collect the treated liquor which is pumped to sludge lagoons. Three 800 gpm centrifugal sludge pumps serve to pump this treated liquor to the lagoons, which are at approximately 270 feet higher elevation than the treatment tanks.

5 Two 730 gal. steel tanks with conventional slow speed paddle mixers are used to mix the lime as a water suspension. Dolomitic lime hydrate is received in bags, cut open by hand and fed to the mixers. Small pumps are used to pump the lime suspension to the treatment tanks.

6 The necessary titrating equipment is provided for the operator to determine the acid and iron content of the incoming flow. A rotometer and recorder measure the incoming flow in the pump line. A pH recorder keeps a running record of the pH of the slurry in the last tank.

7 The very large lagoons allow the suspended solids to settle with the clarified water being drawn off the surface and returned to the creek.

8 This present treatment plant has been in operation since 1945. It was designed on the basis of one hour retention and recirculation time at a flow of 1,100 gpm. It is very evident that this plant also has the very minimum of instrumentation and automatic control equipment. The operator makes his tests at 10 and 15 min. intervals and adds the lime requirement in batches to the first treatment tank. A lime addition chart has been worked out to fit this type of treatment so that the operator, after titrating the waste liquor and reading his flow meter, can read directly the amount of lime required. This chart is adjusted to allow approximately a 5% excess of lime over stoichiometric amounts required. The pH of the treated slurry being pumped to the lagoon is held between 8.5 and 9.0.

a The lime neutralization treatment of these type of wastes on a large scale creates a very real problem--the disposal of large quantities of sludge. A 600,000 cu. yd. lagoon will only take care of these sludges for about four years. The acquiring of land for additional lagoons is an endless and continuing program so that this process can only be used in certain locations. Due to the gelatinous nature of this iron hydroxide sludge, it dries out only for a thin layer on the surface and remains much the same underneath as when settled.

b This treatment plant has served to neutralize all the acid and iron content of the pickling wastes and return the supernatant to the stream. This, of course, is at a cost which seems very excessive when it is realized the treatment costs are considerably more per ton of acid used than the original cost of the acid.

c This plant is now overloaded and a new completely modern treatment facility is being engineered, with the hope that some savings may be obtained.

B Butler Works Neutralization Facility
No. 2 Plant

1 No. 2 Plant of Butler Works is a stainless steel processing plant. The anneal and pickle line is a conventional unit using nitric and hydrofluoric acids for pickling of all grades of stainless steels. The waste treatment plant receives the strong waste acid and rinse waters from one anneal and pickle line, but is designed to also handle wastes from a second anneal and pickle line. In addition to complete treatment of the wastes, this treatment plant also serves as a conservation measure since the clarified water obtained is used as primary rinse for the pickled stainless strip.

2 The rinse waters, and acid wastes resulting from tank overflow, dumps, or draw down, are collected in a 16,000 gal. rubber-lined tank and pumped by means of centrifugal pumps at a rate controlled by a liquid level control valve. At the third-floor level of the treatment plant the acid wastes enter a stainless steel 90° V-Notch weir box for flow measurement and then flow to the bottom of the primary mix tank of 5000-gal. capacity. Here the waste is mixed with a dolomitic lime slurry with the aid of a turbine-type mixer. The neutralized waste then flows by gravity to the bottom of a secondary mix tank where a synthetic polyelectrolyte flocculating aid is added to give a concentration of one ppm. In this tank a slow-speed propeller-type mixer is used to promote flocculation of the precipitate formed.

3 By gravity, the slurry, containing about one-half per cent of undissolved solids (particulate matter), flows to the center well of a clarifier (30 ft. dia. by 15 ft. high) where an additional one ppm. of flocculating aid is added. Settled sludge containing 10% solids is removed from the bottom of the clarifier and filtered by vacuum on two 4-ft. dia. disc filters (65 sq. ft. area) yielding a filter cake that is one-fourth inch thick. Flow of the sludge to the filters is automatically controlled by electrode probe control of the sludge level in the filter pan.

a The clarified water overflows the clarifier to a 19,000 gal. storage tank from which it is pumped to the anneal and pickle process line for use as primary rinse of the pickled stainless steel strip.

b Other equipment at the treatment plant includes two 1700-gal. tanks for preparation and storage of lime slurry. A similar tank is provided for storing dilute 0.04% solution of flocculating aid while a 110-gal. tank is used for preparation of a 0.5% stock solution of flocculating aid.

4 A small-scale pilot plant investigation indicated that the best approach to controlling the lime feed was by determination of pH in the primary mix tank. After the full-scale treatment plant was put into operation, it was soon learned that the control procedure had to be more elaborate than was indicated by pilot plant studies. Subsequently, modifications were made until the present empirical control procedure was derived which has proven to be satisfactory.

a Neutralization of waste acid with lime might seem to be a simple matter, and well it might be if a large excess of lime would be desirable. However, it is necessary to maintain a narrow pH range in the mix tank so as to produce a high-quality water and a settleable and filterable slurry. Also excessive lime usage would increase lime cost and sludge handling.

b The necessary control testing is made at least every half hour by measuring pH in the mix tanks, taking flow readings and determining the total acidity of the waste.

The control calculations consist of three parts.

1) Control, Part I - Use of Nomograph

Knowing the concentration of lime (lbs. CaO/gal.), the flow of acid waste (gpm) and the acidity of the acid waste (lbs. CaO/gal. equivalent), a nomograph is used to obtain the theoretical lime feed (gpm). The flow rate of lime indicated by the nomograph represents the theoretical requirement of lime slurry at the time of sampling.

2) Control, Part II - Lag Time Compensation

Since the nomograph indicates the lime required for the waste at the time of sampling, it does not indicate the imbalance occurring in the treatment plant during the preceding one-half hour of operation. This imbalance may be due to inaccuracies in flow measurement, analysis, changes in lime, etc. normally inherent in this type of operation. However, the greatest deviation from optimum operation is due to the large and rapid changes in concentration of the waste as already indicated. The retention time and/or reaction time in the primary mix tank results in inability to detect changes in the tank early enough to maintain optimum operation. Consequently accurate control of lime feed requires that a calculation of excess or of deficiency of lime present in the primary mix tank be made. This is followed by a corresponding adjustment to the flow setting indicated by the nomograph (Part I).

From pilot plant and full-scale plant operation, a relationship was established between acidity and pH in the primary mix tank. Using this relationship and knowing the volume of the mix tank, calculations can be made to indicate the adjustment of lime required to correct the pH condition in the mix tank.

3) Control, Part III - Theoretical-Practical Compensation

It has already been shown above how an adjustment is made (Part II) for changes in lime demand. This only corrects for deviation in the previous one-half hour of operation. In Part III of the control procedure, another adjustment is made in the lime feed which attempts to anticipate the difference between actual operating conditions and theoretical considerations (nomograph) assuming that the change in waste conditions is continuing to occur approximately as it had in the preceding period.

The theoretical-practical compensation (Part III) is also based on the pH in the primary mix tank, except that it is calculated on the flow of waste instead of the capacity of the mix tank. The setting adjustments in lime flow for Part III are provided. Whereas lime settings calculated under Part I and Part II are independent of previous settings, the settings calculated under Part III are accumulative to previous calculations since the theoretical-practical considerations are assumed to stay on either the plus or the minus side for relatively long operating periods.

In effect Part II of the control procedure lessens the adjustment required for Part II, thus smoothing out the control operation and, consequently, the pH variation throughout the treatment plant.

4) The lime feed adjustments are given in weir splitter settings. A very convenient means of controlling the lime feed is made possible by means of the weir box. With delivery of 30 gpm of lime slurry to the box and an overflow pipe level at 2 in. above the weir, a change of one in the splitter scale is equivalent to .01 gpm. For simplicity of operation all control calculations are given directly in weir splitter settings.

The three settings calculated according to the above description are added together to obtain the weir splitter setting for the next half hour of operation.

5 This manual and empirical approach has proven very successful and economical.

C Middletown Works - Treatment of Rinse Waters - HCL Picklers

1 Armco Steel Corporation, as a part of the Project 600 Expansion Program, is building two new strip picklers at the Middletown Works. These picklers will utilize hydrochloric acid as the pickling medium. These picklers will be the most modern in the steel industry and will be equipped with the best designed squeege rolls and sprays to reduce drag-out losses to a very minimum. Deep well disposal will take care of the spent pickling solutions.

a To comply with the water quality objectives of the Ohio Water Pollution Control Board, Armco proposes to install a complete neutralization and clarification plant to treat the rinse waters produced by these two pickling lines.

b This waste treatment plant will neutralize the free acid, precipitate the iron, and clarify the waste water before discharge to the waters of the state. A brief description of this process and the major equipment to be installed is given below.

2 General description of treatment facilities

a Rinse waters, including fume scrubber water, estimated at 750 gpm per pickle line will be collected at the pickle lines in two 12,000 gal. tanks, one adjacent to each line. Both tanks will be interconnected to pumps which will transfer the waste waters in an overhead pipeline for approximately 1300 ft. to two 45,000 gal. surge tanks which provide one-hour minimum retention. These tanks will be elevated to provide gravity flow through the treatment facilities.

b The first stage of the process consists of limestone neutralization with simultaneous complete oxidation of the ferrous iron in a 23 ft. × 26 ft. × 10 ft. deep combination oxidation - neutralization tank (30 minute minimum retention) with a turbine type surface aerator to provide turbulence and oxygen transfer. The limestone addition will be automatically controlled by a combination of flow and pH requirements.

c The water, containing the newly formed hydroxide floc and the insoluble limestone solids, then flows by gravity into a 14 ft. 6 in. × 30 ft. × 15 ft. deep flocculating tank (30 minute minimum retention) equipped with slow speed mechanical flocculators for mechanical floc development. Coagulant aid chemicals will be added at the flocculating tank for improvement of floc development.

d The floc is subsequently separated from the water in a 50 ft. dia. × 16 ft. deep (less than 1.0 gpm/sq. ft. rise rate) clarifier. A portion of the sludge that is formed will be continuously recirculated back to the aeration mix tank to aid in the floc formation. The remainder of the sludge will be periodically pumped to two 6 ft. dia. × 6 ft. wide endless belt rotary vacuum type filters for dewatering...

The clarified water will flow into a 19 acre lagoon in order to equalize process variations and insure a discharge of constant quality water, suitable for discharge into Dick's Creek.

3 Limestone dust from the Piqua Quarries will be used as the neutralizing chemical. Normal consumption is estimated to be 23 tons per day. Pneumatic trucks will deliver the limestone directly to the storage bins. Dry volumetric feeders will feed proportional to the influent flow and to the alkalinity demand.

a Coagulant aid chemicals, used for improvement of floc development, will be delivered by truck in bags. The chemical will be dispersed into a 0.5% stock solution, then diluted to 0.05% before metering into the floc tank. Two motor control centers will provide control for all process motors in the terminal treatment disposal facility. The motor control centers will be located in a separate enclosed area within the facility.

b Limestone dust rather than hydrated lime is used as the neutralizing agent in order to slow down the rate at which iron is precipitated from solution. This controlled rate of precipitation in the presence of previously formed floc particles and the simultaneous oxidation to ferric iron produces an iron floc that settles much more readily and greatly improves the filtration rate.

IV In summary, the neutralization of steel pickling wastes would appear to be a rather simple chemical process. However, years of research, engineering, and operational experience has demonstrated that what is a relatively simple batch process, in a beaker, is a complicated and difficult control problem when applied to a continuously flowing stream which varies in flow rate, free acid content and iron salts concentration.

A What has been done in the past has at best been only a stop-gap measure and a very expensive one.

B With increasing demands for more rigid water quality requirements, it is obvious that our present technology is woefully lacking in order to design feasible neutralization processes for Steel Pickling Wastes.

This outline was prepared by John E. Barker and Grant A. Pettit, Armco Steel Corporation, Middletown, Ohio.

CHEMICAL-PHYSICAL PROCESSES

I INTRODUCTION

A The most recent advance in the art of sewage treatment is the application of physical-chemical technology to raw sewage treatment. In reality, physical-chemical treatment of sewage is not a completely new technology. Chemical treatment of sewage was widely practiced in England and the United States in the latter portion of the 19th Century. However, this technique gradually fell into disuse with the advent of activated sludge, because activated sludge systems achieved higher degrees of treatment (1). In the 1930's, a number of systems employing physical and chemical treatment in combination were evaluated. These produced treatment superior to primary sedimentation followed by activated sludge (conventional treatment) but at a cost 1.5 to 2 times as great (2). This additional increment of cost discouraged adoption of physical-chemical treatment at that time.

B During the last decade, advances in physical-chemical treatment technology resulting from Environmental Protection Agency-supported research have significantly reduced the cost of physical-chemical treatment. In addition, it is apparent that higher levels of treatment will be required in the future to maintain water quality. As a result of these alterations in conditions, physical-chemical treatment is now an alternative to conventional treatment, especially for situations where significant phosphorus removal is required.

II GOALS OF SEWAGE TREATMENT

A The fundamental goal of sewage treatment is sufficient reduction in the level of pollutants in the wastewater to allow discharge to the environment. The pollutants in sewage are grouped into classes of similar compounds which have the same environmental impact rather than being individually dealt with. At present, the five major pollutant groups of interest are: 1) suspended solids, 2) organic matter as measured by BOD, TOC or COD, 3) phosphorus compounds, 4) nitrogen compounds, and 5) pathogenic microorganisms.

B It is impossible to specify one set of effluent standards which is applicable to all or most situations. However, it is generally agreed that a good quality effluent will have the characteristics given in Table 1. In addition, complete disinfection will be required. As yet, no general agreement on a nitrogen level is in evidence. It must be repeated the goals listed above are not design standards, but are guides in describing a good quality effluent.

TABLE 1.

DESIRED
EFFLUENT
QUALITY

BOD	10 MG/L
COD	60 MG/L
SS	10 MG/L
P	1 MG/L

III THE CLARIFICATION-ADSORPTION PROCESS

A The physical-chemical treatment system which at present is most advanced in development, and which seems the best is the clarification-adsorption system schematically illustrated in Figure 1.

Figure 1.

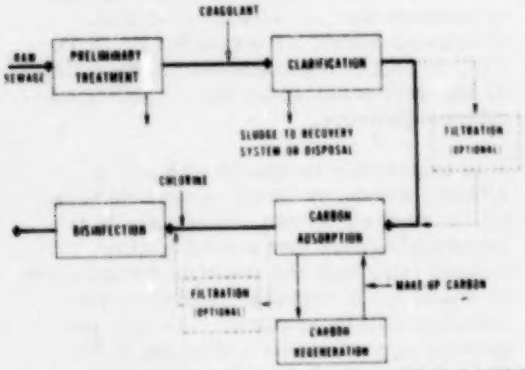


FIG 1 FLOW DIAGRAM OF A PHYSICAL-CHEMICAL TREATMENT SYSTEM

In this system, chemical clarification and filtration are utilized to achieve almost complete suspended and colloidal solids removal. With a high enough dose of the proper chemicals, essentially complete phosphorus removal can also be obtained. The function of the activated carbon step is the removal of soluble organics.

As in any conventional system preliminary screening, grit removal and final disinfection are provided. The filtration step is shown as optional but conservative design dictates its use. The positioning of this step prior to or after carbon adsorption is dictated by the type of waste-carbon contacting system provided. The three steps of chemical clarification, filtration and carbon adsorption will be discussed in some detail below.

This system does not provide ammonia or nitrate-nitrogen removal. Physical-chemical methods for soluble nitrogen removal are covered in another lecture of this symposium. Any of these nitrogen removal methods can be integrated into the clarification-adsorption system.

B Chemical Clarification

1 Chemical clarification provides the bulk of the pollutant removal achieved by this type of treatment system. In this unit operation an appropriate chemical is dosed to the wastewater and the mixture is flocculated and settled. All of these steps can be conducted in independent units, or combined into a single unit which is usually referred to as solids-contact clarifier.

2 Chemicals which have been successfully used to clarify raw sewage include organic polymers (3), iron salts (4), aluminum salts (5), and lime (6) (7). The inorganic coagulants have the advantage of providing for phosphorus removal. At present there is no rational method for predicting the dose of chemical required. For planning purposes, jar tests are suggested. Fortunately, field control of the coagulant dose is possible. For all coagulants except lime the suggested method is monitoring of the clarifier effluent turbidity. Good clarification is always obtained when sufficient chemical is added to provide good phosphorus removal. With lime as the coagulant, excellent control is obtained by pH measurement. The pH required to achieve good clarification and phosphorus removal is dependent on the chemical characteristics of the sewage. In areas where the alkalinity and hardness are low, the high lime process in which the pH is raised to approximately 11.5 is required. Generally, two-stage precipitation with intermediate recarbonation is utilized. In hard water, high alkalinity areas a low lime single-stage precipitation at pH 9.5 to 10 is sufficient.

Table 2 illustrates the treatment obtained with chemical clarification in pilot plants at a variety of locations. In addition to the expected high levels of suspended solids and phosphorus removal significant organic removal was obtained. Based on these data and others it can be expected that chemical clarification of raw sewage will consistently yield organic removal in the 65-75 percent range. With this degree of organic removal from chemical coagulation the carbon need provide only a small increment of additional removal to match the performance of a good secondary treatment system.

TABLE 2
ACHIEVEMENTS OF CHEMICAL CLARIFICATION

PLANT	CHEMICAL	ORGANIC REMOVAL %	SS REMOVAL %	P REMOVAL %
EWING-LAWRENCE	170 mg/l $FeCl_3$	80	95	90
NEW ROCHELLE (ZM)	LIME pH 11.5	80	98	98
WESTGATE, VA.	125 mg/l $FeCl_3$	70	-	-
SALT LAKE CITY	80-100mg/l $FeCl_3$	75	-	80
BLUE PLAINS	LIME pH 11.5	80	90	95

3 Sludge disposal plays a dominant role in the economics of any chemical clarification system. Only limited data on the characteristics of sludges resulting from the chemical treatment of raw sewage are available. These data indicate that with iron or aluminum salts as coagulants:

a The resulting sludge volume sometimes exceeds and sometimes is less than primary sludge from the same sewage.

b The chemical sludge is more difficult to dewater in a vacuum filter than the corresponding primary sludge.

c With lime as the coagulation chemical dewatering is extremely rapid just by gravity thickening. Eimco (8) reported lime-raw sewage sludge solids concentrations of 15% to 25% after gravity thickening.

4 In addition to yielding a sludge amenable to rapid and easy dewatering, lime is the only coagulation chemical which can be economically recovered. Recalcining the lime sludge in a furnace has been successfully conducted in a tertiary plant at South Lake Tahoe and has been state-of-the-art in water softening plants for a considerable period of time (9). In addition to regenerating the lime, the organic solids are incinerated, thereby accomplishing ultimate disposal of the sludge. For these reasons, it is anticipated that lime will be the coagulant of choice for most situations.

5 Design criteria for the coagulation equipment is similar to that used in water treatment plants. A flash mix of one minute, flocculation for 15 to 30 minutes and sedimentation at upflow rates of 0.5 and 1.0 gpm/ft^2.

C Carbon Adsorption Systems

1 The role of the carbon adsorption step is the removal of soluble organics from the wastewater after coagulation has removed particulates. The total organic removal achieved by the combination of clarification and carbon adsorption at several physical-chemical pilot plants is illustrated in Table 3. It can be seen that not only is the removal achieved quite high (95%+) but equally important the residual organics after treatment are quite low. These effluents are superior to that listed in Table 1.

Table 3.

TOTAL TREATMENT P-C PLANTS

PLANT	ORGANIC REMOVAL %	EFFLUENT CONCENTRATION
BLUE PLAINS	95-98	TOC = 6
LEBANON	95	TOC = 11
EWING-LAWRENCE	95-98	TOC = 3-5
NEW ROCHELLE	95	COD = 8

2 The results reported in Table 3 were obtained with carbon contacting systems employing granular carbon. In such systems, the waste is passed either upward or downward through columns containing the carbon. Downflow columns function as packed beds and accomplish filtration of the wastewater. Flow rates of 2 gpm/ft^2 to 8 gpm/ft^2 have been employed. In this flow range essentially equivalent adsorption efficiency is obtained provided the same contact time is employed. At flow rates below 2 gpm/ft^2 adsorption efficiency is reduced, while at flow rates above 8 gpm/ft^2 excessive pressure drop takes place. Contact times employed are in the range of 30 minutes to 60 minutes on an empty bed basis. In general increases in contact time up to about 30 minutes yield proportionate increases in organic removal. Beyond 30 minutes the rate of increase falls off with increases in contact time becoming negligible at 60 minutes. Gravity beds are commonly used for lower flow rates, pressure vessels for higher flow rates. The pressure vessel is more expensive but requires less land and accepts flow variations better.

3 Provision must be made to periodically backwash downflow carbon beds because they gradually collect suspended solids. In addition, biological growth takes place on the carbon granules and tends to clog the bed. It is advisable to include a surface wash and air scour to be assured of removal of the gelatinous biological growth.

4 Backwash of the carbon beds satisfactorily relieves clogging but does not completely remove the biological growth. Significant biological activity is manifest in the carbon beds at most times. This leads to the development of anaerobic conditions in the carbon bed and generation of sulfides. Aeration of the column feed has been utilized to prevent anaerobic conditions, but this produced so much biological growth that excessive backwash was required.

5 In an attempt to overcome these difficulties, upflow carbon columns have been operated in a slightly expanded mode (about 10% expansion). This allows for significant accumulation of biological activity on the carbon granule with little increase in head loss. Consequently, aerobic conditions can be maintained and sulfide generation prevented.

6 Backwash facilities are necessary for expanded beds to remove excess growth. Flow rate range which can be used is more restricted than with packed bed systems. With the commercial sizes of carbon available, (8x30 mesh or 16x40 mesh) flow rates above 4 to 5 gpm/ft^2 are required to achieve the proper degree of expansion. Care must be exercised to avoid hydraulic surges which could wash carbon out of the system. The filtration section of the physical-chemical treatment plant must follow carbon contact when the expanded bed system is used.

7 The latest carbon contacting scheme to be applied to waste treatment utilizes powdered carbon (particle size below 200 mesh). This procedure provides for a mixture of a carbon slurry and the wastewater in a Reactor-Clarifier. Polymer addition is generally required to achieve a good gravity separation of the carbon from the wastewater following contact. The potential advantages of this sytem are the use of a cheaper carbon (10¢ per pound vs. 30¢ per pound for granular carbon) and a simpler type of contacting system.

8 A critical aspect of the design of any carbon contacting system is the expected capacity of the carbon for the organics. In the chemical processing industries, this is evaluated by running

adsorption isotherm tests. In the waste treatment field, isotherms are of limited utility because the biological activity which develops on the carbon tends to greatly enhance its apparent capacity for organic removal.

D Design of Carbon Adsorption Facilities

1 The role of the design engineer is to utilize the greatest use of the carbon regardless of capacity. Countercurrent contact favors good effluents and carbon utilization. This is achieved by having the waste flow through a number of contactors or stages in series in one direction, while the carbon moves in the opposite direction. In the powdered carbon contacting system, this is exactly the procedure used. With granular carbon, this procedure cannot be used as undesirable attrition losses will take place. When an undesirable effluent is obtained, the lead contactor is removed from service and a spare contactor with fresh carbon placed at the end of the line. Each contactor is then moved up one position in the line. This is accomplished by piping and valving a series of columns to shift the inflow and outflow points rather than physically moving the columns. As the number of stages increases, the piping and valving arrangement becomes more complex and costly. In design, a compromise between the advantage of adding another stage to more closely approach the highest use of the carbon capacity, and the cost of each additional stage must be achieved.

2 An alternate arrangement provides parallel flow through a number of identical contactors. Each is at a different stage of exhaustion and produces a slightly different effluent quality. These individual effluents are blended to produce the final product.

Table 4 reviews the various factors which must be considered in designing any carbon removal system.

Table 4.

CONSIDERATIONS IN CARBON TREATMENT DESIGN

1. TYPE OF CARBON-GRANULAR OR POWDERED
2. CONTACT TIME
3. FLOW RATE
4. CONFIGURATION-SERIES OR PARALLEL
5. NUMBER OF STAGES
6. FLOW DIRECTION - PACKED OR EXPANDED
7. HYDRAULIC FORCE - PUMPED OR GRAVITY
8. ORGANIC CAPACITY

---

3 Carbon capacities obtained in field operation at various pilot plants are given in Table 5. The waste, effluent criteria, number of contact stages, etc., varied from plant to plant giving some spread in the results. These capacities are expressed as pounts of organics removed (either as COD or TOC) per pound of carbon. For general planning purposes, a capacity of 0.5 pounds of COD per pound of carbon is reasonable. This is approximately equivalent to a requirement of 500 pounds of activated carbon per million gallons of sewage treated.

Table 5.

Carbon Capcity in P-C Treatment Plants

Plant	Carbon Capacity	
	LBS TOC LB A.C.	LBS COD LB A.C.
Blue Plains	0.15	0.41
Ewing-Lawrence	0.3	-
New Rochelle (ZM)	-	0.6
Lebanon	0.22	0.5

AC = Activated Carbon

4 A carbon requirement at this level would be prohibitively expensive if regeneration and reuse of the exhausted carbon were not possible. At present, a technically and economically feasible method is available for the regeneration of granular activated carbon. This method requires heating of the carbon in a multi-hearth furnace in the presence of steam to 1750°F. This treatment burns away the adsorbed and trapped organics. During a regeneration cycle, some of the carbon is physically lost by burning and attrition, and some of each particle's capacity is lost by alteration of surface properties. The overall loss expressed as percent by weight of virgin carbon required to restore the total original capacity of the batch ranges from 5 to 10 percent (10). Thus, for planning purposes carbon makeup requirements at a plant should range from 25 to 50 lbs per million gallons of sewage treated.

5 At present, experiments on a fluidized bed regeneration system for powdered carbon are moving into the large-scale pilot stage. Successful completion of these tests will be a big step forward in making a powdered carbon system a technical and economic reality. The key factor will be maintaining the carbon loss at a low enough level during the regeneration.

IV DESCRIPTION AND PERFORMANCE OF SPECIFIC PHYSICAL-CHEMICAL PILOT PLANTS

A Ewing-Lawrence (4)

For the last several years, FMC Corporation has been conducting studies of physical-chemical treatment at the Ewing-Lawrence Treatment Plant near Princeton, N.J. Figure 2 illustrates the clarification section of the plant. These units were somewhat overdesigned to insure a good feed to the adsorption section of the plant, as the major purpose of the research was to evaluate carbon performance. Figure 3 is a schematic of the overall plant. Packed bed versus expanded bed carbon contact in parallel was studied at this plant. Figure 4 indicates that the performance of the packed bed contactor was slightly superior to that of the expanded bed contactors. However, the investigators indicated that the advantage was not sufficient to offset the need to backwash more frequently and the potential difficulties from anaerobic conditions in the carbon beds. Figure 5 illustrates the BOD removal obtained over a 3-1/2 month period. It can be seen that despite considerable variation in influent strength a consistently good effluent was produced. This figure also reiterates that the bulk of the treatment is accomplished in the chemical clarification step.

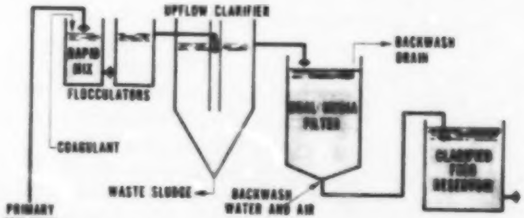
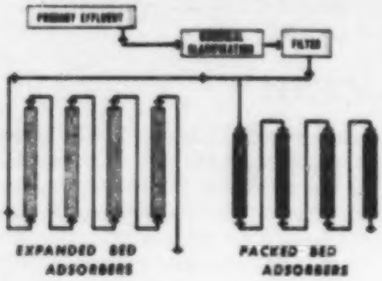


FIG. 2
FLOW DIAGRAM OF CLARIFICATION SYSTEM

FIG. 3
EXPERIMENTAL SET-UP
FOR 24 FT. CARBON BEDS



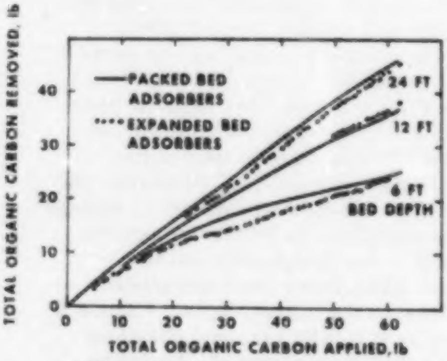


FIGURE 4 Cumulative sorption of total organic carbon for packed bed and expanded - bed adsorbers as a function of TOC applied. (Lb × 0.454 = kg; ft × 0.3 = m.)

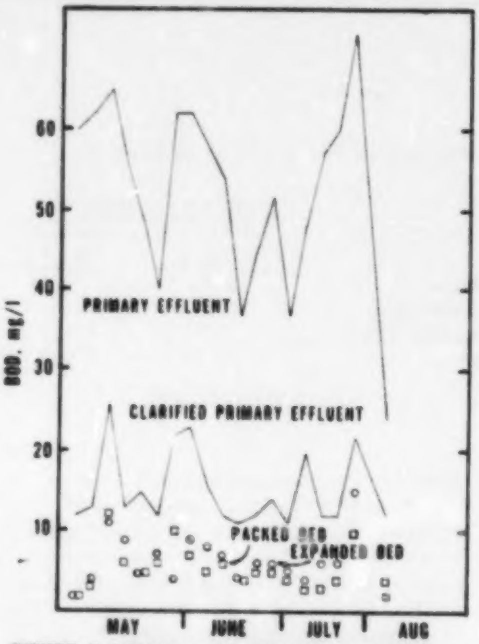


FIGURE 5 REMOVAL OF BOD BY CHEMICAL CLARIFICATION AND ACTIVATED CARBON

B **Blue Plains (7)**

At the Blue Plains treatment plant in Washington, D.C., a pilot physical-chemical treatment system is being operated as part of a joint effort of EPA and the District of Columbia. Figure 6 is a schematic of the treatment system. Two-stage high lime clarification is provided with a small dose of ferric chloride in the second stage for flocculation of calcium carbonate. This stage of the plant has a capacity of 100,000 gal/day. The filtration, ion exchange and downflow two-stage carbon beds have a capacity of 50,000 gal/day. This plant is highly automated and thus runs with a minimum of manual control. For example, the lime dose is automatically set by monitoring the pH and alkalinity in the clarifiers, and backwash of the filters, ion exchange columns, and carbon columns is automatically initiated by pressure drop and/or a time cycle.

Figure 7 illustrates the treatment performance obtained at this plant for a variety of pollution control parameters. Nitrogen removal was obtained by the use of an ion exchange process with a zeolite which has a high affinity for ammonium ion. Again, these data indicate that the bulk of the work is done by the clarification step with the filter and carbon columns serving as polishing devices. Table 6 gives the average effluent characteristics for this installation. This effluent is far better in quality than normal secondary effluent.

FIG. 6
INDEPENDENT PHYSICAL CHEMICAL TREATMENT
LIME PRECIPATION

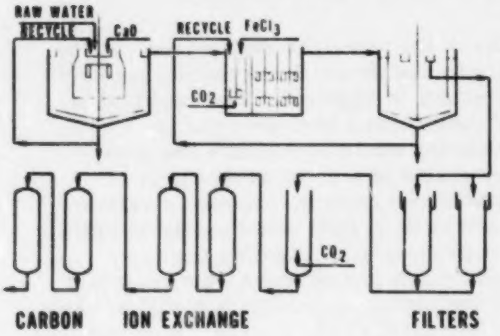


FIG. 7 REMOVAL EFFICIENCI‹S
PHYSICAL CHEMICAL TREA‹MENT
BLUE PLAINS PILOT PL‹NT

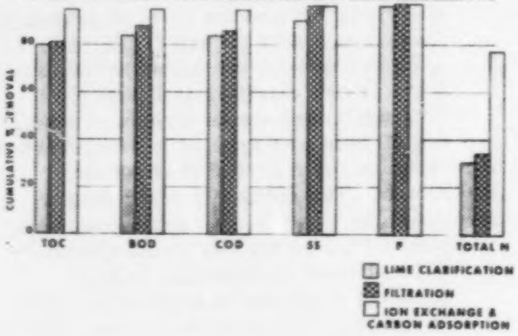


TABLE 6

EFFLUENT QUALITY - P - C
PILOT PLANT AT BLUE PLAINS

TOC	6 mg/1
BOD	5 mg/1
COD	13 mg/1
SS	5 mg/1
TOTAL P	0.15 mg/1
TOTAL N	4.6 mg/1

C Salt Lake City, Utah (8)

Under contract between EPA and Eimco Corporation, an evaluation is being conducted of a physical-chemical treatment system employing powdered carbon contact after chemical clarification. Figure 8 illustrates the pilot plant. Two countercurrent stages of carbon contact in Reactor-Clarifier are provided following chemical clarification. Some results with lime as the coagulant are given in Table 7. These results are not quite as good as in the plants using granular carbon discussed previously. The effluent, however, must still be classified as of good quality. One potential advantage of this contacting system is the ability to pace the carbon dose to the organic demand. Evaluation of powdered carbon regeneration will take place at this installation. The spent carbon will be dewatered on a vacuum filter prior to being fed to the fluid bed furnace.

TABLE 7

Powdered Carbon Pilot Plant
Operating Conditions
Flow Rate 50 Gal/Min
Chemical 425 mg/l Lime TO pH 10.8
Carbon 150 mg/l + 0.4 mg/l polymer

RESULTS

	COD	BOD	SS	P
Raw Sewage	222	144	200	7.3
Clarified Effluent	65	47	28	1.4
Final Effluent	35	13	7	0.4

ALL RESULTS GIVEN IN mg/l

D Rocky River, Ohio (3)

Several studies have been made utilizing polymer addition to existing primary plants followed by small-scale pilot carbon adsorption. One such study was done at the 10 MGD primary facility at Rocky River, Ohio. An anionic polymer was added to the existing primary clarifier at a dosage of 0.3 mg/1, and a side stream of clarified effluent was applied to small carbon columns for a period of about one month. The summary of the data is shown in Table 8. It can be seen that, even with less than optimum clarification, effluent comparable to good secondary effluent was produced with 33 minutes carbon contact time. On the basis of this preliminary work, the City of Rocky River applied for and was awarded a Research and Development Grant from EPA to help support a full-scale investigation of the clarification-adsorption process for secondary treatment.

1 One of the principal motivations for the city to use physical-chemical treatment is shown in Figure 9. The installation of conventional activated sludge facilities would necessitate the condemnation of a considerable area of expensive property, whereas a carbon adsorption system could easily fit into the existing site. Testing has been undertaken to determine what coagulant or combination of chemicals will be used in the clarification system. If phosphorus removal is required, an inorganic coagulant will necessarily be the choice.

FIGURE 8

PHYSICAL/CHEMICAL TREATMENT PROCESS

EIMCO
ENVIROTECH

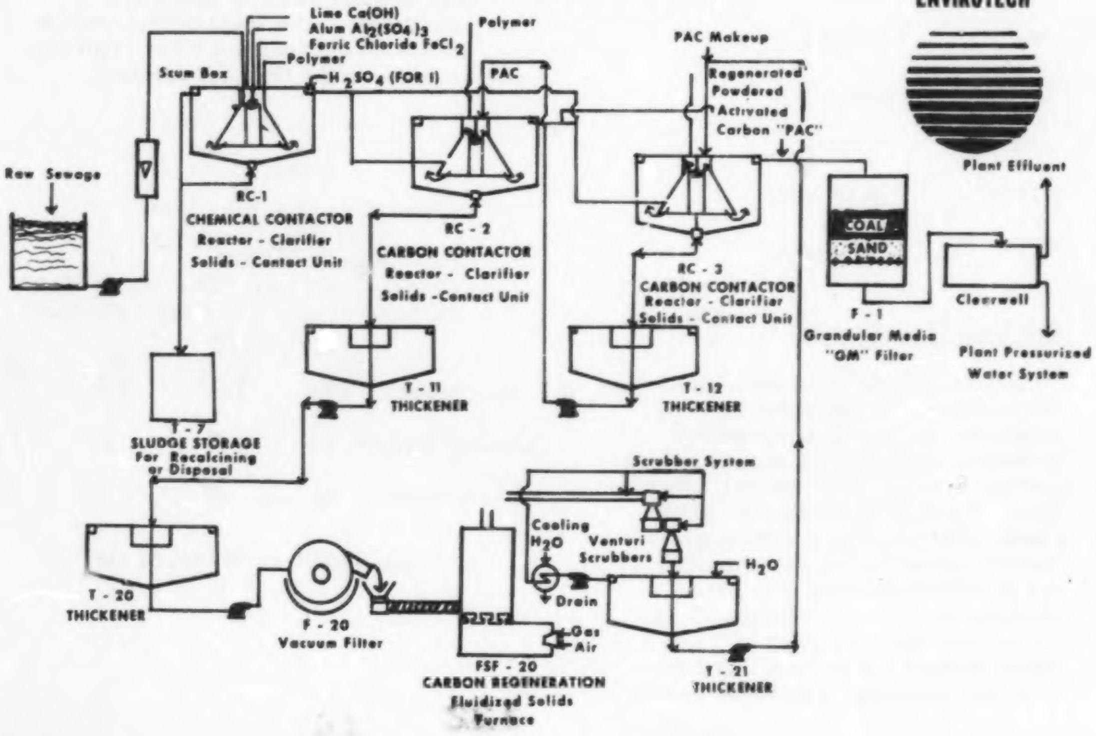

Lime Ca(OH)
Alum Al2(SO4)3
Ferric Chloride FeCl2
Polymer
Polymer
Scum Box
H2SO4 (FOR I)
PAC
PAC Makeup
Regenerated Powdered Activated Carbon "PAC"
Raw Sewage
RC-1
CHEMICAL CONTACTOR
Reactor - Clarifier
Solids - Contact Unit
RC - 2
CARBON CONTACTOR
Reactor - Clarifier
Solids - Contact Unit
RC - 3
CARBON CONTACTOR
Reactor - Clarifier
Solids - Contact Unit
COAL
SAND
F - 1
Granular Media "GM" Filter
Plant Effluent
Clearwell
Plant Pressurized Water System
T - 7
SLUDGE STORAGE
For Recalcining or Disposal
T - 11
THICKENER
T - 12
THICKENER
Scrubber System
Cooling H2O
Venturi Scrubbers
H2O
Drain
Gas
Air
T - 20
THICKENER
F - 20
Vacuum Filter
FSF - 20
CARBON REGENERATION
Fluidized Solids Furnace
T - 21
THICKENER

Figure 9.

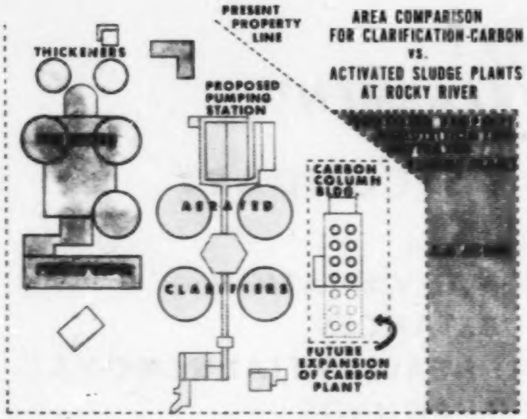

PRESENT PROPERTY LINE
AREA COMPARISON FOR CLARIFICATION-CARBON VS. ACTIVATED SLUDGE PLANTS AT ROCKY RIVER
THICKENERS
PROPOSED PUMPING STATION
CARBON COLUMN BLDG.
AERATED
CLARIFIERS
FUTURE EXPANSION OF CARBON PLANT

TABLE 8

ROCKY RIVER
WASTE TREATMENT PLANT
CLARIFICATION-CARBON PROCESS

	Raw	Polymer Clarification	Carbon Contact Time, Minutes			Percent Removed
			14	23.4	32.6	
SUSPENDED SOLIDS, mg/l	107	65	13	15	7	93.3
BOD, mg/l	118	57	21	11	8	93.3
COD, mg/l	235	177	67	50	44	81.3

V ADVANTAGES OF PHYSICAL-CHEMICAL VS. CONVENTIONAL TREATMENT

Perhaps the most important advantage is the stability of operation provided by a treatment system based on physical and chemical technology. Biological systems are notoriously sensitive to changes in environmental conditions. If a toxic material or a hydraulic peak occurs, not only will the efficacy of the biological plant drop off but recovery may take several days to several weeks. In a physical-chemical plant, the filtration system backs up the clarifier and the carbon system backs up the first two; thus, upsets should be unlikely. In addition, it can be expected that an immediate recovery of the plant will take place once the source of upset is eliminated, or corrections are applied. This inherent stability of performance is also reflected in greater design and operational flexibility. Whole sections of a physical-chemical plant can be cut in or out of the process stream as required, and a temporary overload can be absorbed with little effect. A list of many of the major advantages of a physical-chemical system is given in Table 9. Most have been discussed at some point in this paper.

VI COST ESTIMATES

One of the uncertain factors concerning physical-chemical treatment is the cost of the process. Definitive data will not be available until large-scale plants have been built and are in operation for several years. Even then, local conditions may significantly affect the actual costs. Smith (11) has taken the available information from pilot plants and preliminary designs of several proposed large-scale plants and has made cost estimates for various size plants referenced to October 1970. Amortization was 6 percent for 24 years. These are presented in Table 10. Note that ranges are given for each plant size. These ranges represent the spread of data available. As a comparison Smith's estimate for primary and secondary treatment with sludge incineration is 16.5 cents per 1000 gallons at the 10 MGD level. With the addition of single stage lime for phosphorus removal, the cost would rise to 23.5 cents per 1000 gallons which is essentially the same as physical-chemical treatment.

TABLE 9

ADVANTAGES OF PHYSICAL-CHEMICAL TREATMENT VS. CONVENTIONAL PRIMARY + SECONDARY

1. LESS AREA REQUIREMENT-½ TO ¼
2. LOWER SENSITIVITY TO DIURNAL VARIATION
3. NOT AFFECTED BY TOXIC SUBSTANCES
4. POTENTIAL FOR SIGNIFICANT HEAVY METAL REMOVAL
5. SUPERIOR REMOVAL OF P COMPOUNDS
6. GREATER FLEXIBILITY IN DESIGN AND OPERATION
7. SUPERIOR ORGANIC REMOVAL

TABLE 10

PRELIMINARY COST ESTIMATE PHYSICAL - CHEMICAL TREATMENT

Total Amortization + O&M, cents per 1000 gallons

PLANT SIZE, MGD	5	10	100
CHEMICAL CLARIFICATION *	9.5 - 13.5	7.3 - 9.6	4.0 - 5,3
CARBON ADSORPTION	11.5 - 18.0	9.1 - 13.5	4.5 - 7.8
FILTRATION	2.9 - 4.5	2.1 - 3.3	1.0 - 1.4
TOTAL	23.9 - 36.0	18.5 - 26.4	9.5 - 14.5

* Two - stage lime recalcination of sludge

TABLE 11
PHYSICAL CHEMICAL TREATMENT PLANTS

SITE	CAPACITY	STATUS
Rocky River, Ohio	10	Bids taken
Painesville, Ohio	5	Design
Cleveland, Ohio	10	Design
Fitchburg, Massachusetts	15	Design
Waterford, New York	2	Planned
Cortland, New York	10	Planned
Clay, New York	10	Planned
Niagara Falls, New York	60	Planned
Garland, Texas	30	Design
Owosso, Michigan	6	Design

FUTURE DEVELOPMENTS

As a result of the advantages of physical-chemical treatment discussed above and the favorable economic comparison, a number of full-scale treatment plants are being planned or designed. These are listed in Table 11. Only the first two, Rocky River and Painesville, Ohio, will receive Federal research funds. All the others are being planned with no expectation of Federal funds other than the normal construction grant.

This outline was prepared by I. J. Kugelman and J. M. Cohen, Sanitary Engineer and Chief respectively, Physical-Chemical Treatment Research Program, Advanced Waste Treatment Research Laboratory, RATWRC, NERC, EPA, Cincinnati, OH 45268.

SECTION V DEWATERING AND DISPOSAL

	Outline Number
Sludge Drying and Incineration	25
Sludge Combustion	26
Ultimate Disposal to the Environment	27

SLUDGE DRYING AND INCINERATION

I INTRODUCTION

A Most methods of sewage treatment practiced today result in the accumulation of large volumes of sludge, a mixture of solids and water. Final disposal of this material is one of the more difficult problems facing those involved in treatment plant design and operation.

B Total sludge handling costs (including digestion and/or vacuum drying) may represent 25 to 50 percent of a treatment plant's total capital and operating cost.

C Two primary methods of handling sludge for final disposal are:

1 Drying

2 Incineration

II SLUDGE DRYING

A Drying of sewage sludges has several attractive aspects. For small plants located in favorable climates, these include low capital and operating costs. The same statement is not true of large treatment plants because of the complexity of the processes required and the volumes to be handled.

B Two methods most commonly employed for sludge drying are:

1 Air-Drying

2 Heat-Drying

C Air-drying of sludges is most applicable in small to medium sized plants with considerable space available. Sludge can be air-dried by:

1 Discharge of sludge to sludge lagoons

2 Discharge to sludge drying beds

D The more common practice is the use of sludge drying beds.

1 Sludge drying beds usually consist of graded layers of gravel or crushed stone beneath four to six inches of filter sand. Agricultural tile is often used as an underdrain material. Drying is by evaporation and percolation.

2 Beds are normally subdivided to suit plant operation. The maximum dimensions which are likely to be encountered are 20 ft. by 100 ft.

3 Sludge is usually discharged to the beds from a single outlet. Surface slope is usually 0.5 percent or less.

4 In the northern parts of the United States, drying of about five applications of 8-inch blankets of wet digested sludge, annually, is common. This can be increased by the use of a glass enclosure.

5 Bed-dried sludge contains about 40 percent solids. The volume is about one-half that of the wet sludge.

6 Sludge is removed from the drying beds by hand forking or by mechanical sludge loaders or strippers.

E Advantages and disadvantages of air-drying sludge are as follows:

1 Advantages

a Simple

b Low operating and capital costs

c No chemicals required

2 Limitations

a Dependent upon climactic conditions

b Requires a well-digested sludge (odors can be serious problem with other sludges).

c May require considerable hand labor

d Sometimes difficult of final disposal

F An alternative to air-dried sludge is the use of heat-drying. This process, which involves the use of outside sources of fuel to apply heat for dewatering sludge, is most likely to be encountered in larger communities where land costs and sludge volumes are factors making air-drying practices infeasible.

G Any decision to heat-dry sludge must include the assumption that a market exists for the sale of the dried sludge. This is often not the case. Any plant being designed for heat-drying should also include provision for sludge incineration.

1 Because of the extra fuel required, heat-drying of sludge exceeds the cost of incineration. This additional cost must be offset by the sale of the sludge as fertilizer or soil conditioner. The scale of most heat-drying installations makes a firm contract for bulk sales necessary.

H Units used to dry sludges include the types listed below. Mechanical dewatering of the sludge usually precedes the drying process.

1 Flash drying - The most commonly used for drying sewage sludges, this process involves the instantaneous removal of moisture from solids by contact with a hot gas stream. The process includes blending wet filter cake with previously dried sludge, violent mixing of the semi-dry sludge with hot gases (1300° F) in a cage mill, and separation of the sludge from the gas in a cyclone. Vapors are passed through preheaters (1200° F) for odor control.

2 Multiple hearth furnaces - Basically a sludge incineration unit, these units have been adapted for drying by reversing gas flow and adding heat at a different point in the furnace. (More descriptive information in Section IV-F-1).

3 Rotary dryers - These are basically long steel cylinders revolving at 4 to 8 rpm. Hot gas and a mixture of sludge cake and dried sludge are added at one end. Baffles or flights break up the sludge as it moves through the dryer.

4 Atomized drying - For this process, liquid sludge is sprayed into a vertical tower through which hot gases are passed downward. The water is evaporated from the atomized particles and passes off with the hot gases as the dried sludge drops to the bottom of the tower.

I Any decision to design or operate a sludge drying facility must be based upon the economics of the specific situation. Heat-drying requires the burning of significant quantities of oil, gas or coal. The marketing demands for the product are unreliable and often unattractive.

III SEWAGE SLUDGE AS A FERTILIZER

A Many chemical elements are essential to plant growth. Included among those derived from the soil are nitrogen, phosphorus, potassium, calcium, magnesium, sulfur and iron.

B Fertilizers are generally rated on their content of three constituents.

1 Nitrogen (expressed as N) promotes the growth of leaf and stem.

2 Phosphorus (expressed as phosphoric acid, P_2O_5) stimulates root growth, hastens ripening and increases disease resistance.

3 Potassium (expressed as potash, K_2O) encourages vigorous growth, develops the woody parts of stems and is needed for chlorophyll formation. Potash does delay ripening, however.

C Sewage sludges are generally low in all of these. Table I, following, gives a comparison of sewage sludge with several commonly used fertilizers. Digestion can reduce the values given for sludges by up to 50 percent.

D A quick review of Table I shows that sewage sludges do not compare favorably, especially with commercial fertilizers. Primary sludges are primarily useful as a "filler" material in commercial fertilizers. Other sludges are more valuable as soil conditioners. Often, fortification is required.

E Most treatment plants with heat drying equipment have changed to incineration because of marketing economics. Very few cities have been successful in this venture; those that have do not claim wide financial success.

F Dried sludge is suitable for lawns, shrubs, flowers, and trees. When used on vegetable crops, the edible portion should be above ground and the crops cooked before eating. Unnecessary handling should be avoided.

IV SLUDGE INCINERATION

A Sludge incineration has been a standard practice for many years. It presents a sanitary method for ultimate disposal of reduced volumes. The economics of the combustion process appear more favorable each year.

B Parameters important to the incineration process include:

1 Moisture

2 Volatile content

3 Inerts

4 Calorific value

C As a general rule, the thermal value of sewage sludges is considered to be 10,000 BTU per pound of volatile solids.

TABLE I

PLANT FOOD CONSTITUENTS IN SLUDGES COMPARED TO FERTILIZERS

	Nitrogen (N)	Phosphates (P_2O_5)	Potassium (K_2O)
Cow Manure	2.8%	0.8%	2.5%
Horse Manure	2.6	1.1	2.4
Plain Sedimentation Sludge	1.0 - 5.0	1.0 - 3.0	0.1 - 0.3
Activated Sludge	3.0 - 6.0	1.5 - 3.0	0.2 - 0.3
Trickling Filter Humus	1.5 - 5.0	1.5 - 3.0	0.2 - 0.3
Commercial Fertilizer	2 - 20	6 - 20	4 - 20

D Combustion of sewage sludges is always is always preceded by drying. The total process includes:

  1 Raising the temperature of the feed sludge to 212° F

  2 Evaporating water from the sludge

  3 Increasing the water vapor and air temperature of the gas

  4 Increasing the temperature of the dried sludge volatiles to the ignition point

  5 Cooling the ash for subsequent handling

E Sludge burned in a furnace emits heat. The difference between the heat generated and heat lost is available for heating incoming air. Self-sustained combustion is sometimes possible.

F Units commonly used for sludge incineration include:

  1 Multiple hearth incinerators - The most popular incinerator in use, these units consist of a circular steel shell surrounding a number (4 to 11) of solid refractory hearths and a central rotating shaft to which rabble arms are attached. Sizes vary depending on the installation. Sludge cake enters at the top hearth, from which it is rabbled center-to-side openings, side-to-center openings, from hearth to hearth. Drying occurs on the upper hearths, incineration on the center hearths, and cooling on the lower hearths.

    a Incineration is at 1200° - 1500° F

    b Ash removed hydraulically, pneumatically or mechanically

    c Units are simple, durable and flexible

  2 Flash drying incineration - Following the flash drying operation discussed earlier, the dried sludge is sometimes blown into a furnace in a manner similar to powdered fuel. Temperatures near 1400° F are maintained. These units are rarely installed for incineration today because of their complexity. Most installations are carry-overs from drying operations.

  3 Fluidized bed - A fairly recent development, this involves the introduction of sludge particles into a bed of fluidized sand supported by upward moving air. The reactor serves as a heat reservoir where rapid mixing of the sludge throughout the bed allows rapid heat transfer. Advantages claimed for the system are small area requirements, low operating expense and high efficiency.

  4 Wet oxidation - A multiple step process, this includes:

    a Grinding of thickened sludge

    b Pressurization of sludge

    c Preheating of sludge in heat exchangers

    d Mixture with air and injection into reactor

    e Oxidation as sludge-air mixture follows baffled path through reactor

    f Cooling of reactor effluent (through heat exchangers)

    g Gas-liquid separation

    h Ash-liquid separation

    i Ash dewatering

  Construction and operation costs are high. Engineers are not agreed on relative merits of the system.

G Sludge incineration becomes an increasingly popular method of disposal as volumes increase and land areas become less available. Advantages of incineration include:

  1 Large reductions of volumes

  2 Production of an inert ash

  3 Sterilization

V SUMMARY

Every sewage treatment plant is faced, not only with the problem of sewage treatment, but also the pressing problem of sludge disposal. Small plants often can conveniently dispose of the material by dewatering on drying beds. Larger communities are faced with a selection of drying or incineration techniques of various complexity. Economics is a prime factor. Current trends are toward incineration. Multiple hearth incinerators are most commonly used for this purpose.

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SLUDGE COMBUSTION

I INTRODUCTION

A Incineration of municipal and industrial refuse has been a standard practice for many years. The combustion of semi-solid sewage and industrial waste sludge is a relatively recent innovation. Dearborn, Michigan, installed the first full-scale sewage sludge incinerator in 1935.(287) 2 Sludge combustion is becoming increasingly popular as land areas for sand beds, lagoons, and landfills become more difficult to find and more expensive. The land situation is magnified by ever-increasing volumes of sludge to dispose of and by the encroachment of urban neighborhoods on land disposal areas. There is no doubt that sludge combustion will in the future be adopted by more and more industries and cities because it represents a sanitary method for ultimate sludge disposal (at least for the organic portion of the sludge) in a relatively small land area. For many industries and cities, incineration will provide the only practical answer to sludge disposal.

B Incineration is practiced for two basic purposes, volume reduction and solids sterilization. Fulfilling these purposes is expensive and it may cause an air pollution problem. But the economics of combustion appear more favorable each year as the alternative sludge disposal methods become more expensive. Air pollution problems can be solved by proper equipment design and operation.

II SLUDGE CHARACTERISTICS

A Russell says the following sludge parameters are most important in the incineration process: (1) moisture, (2) volatiles, (3) inerts, and (4) calorific value.(65d) 2 Of the above, moisture is the principal characteristic over which the treatment plant operator has some control. Moisture is generally reduced by mechanical sludge-dewatering techniques before incineration. It is important because of the thermal load it imposes on the incineration process with consequent effects on self-sustained sludge combustion.

B Volatile and inert materials affect the calorie or Btu value of the sludge. They are, to some extent, controlled by other treatment processes such as degritting, mechanical dewatering, and sludge digestion. Almost all of the combustibles are present in the sludge as volatiles, much of it in the form of grease. The volatile percentage and, therefore, the heat value can vary widely, so incineration equipment must be designed to handle a broad range of values.

1 Table 19.1 by Owen describes the most important incineration parameters for many of the solids generated at a sewage treatment plant.(321)

2 As a general rule, the thermal value of sewage sludge is considered to be 10,000 Btu per pound of volatile solids. If the ultimate analysis is known, Owen claimed that the heat value can be precisely computed by using the DuLong formula:(321)

$$Q = 14,600\ C + 62,000\ (H - \frac{O}{8})$$

where Q = Btu/lb.
C = % carbon
H = % hydrogen
O = % oxygen

III THEORY

A Incineration processes involve two steps: (1) drying and (2) combustion. In addition to fuel and air; time, temperature, and turbulence are necessary for a complete reaction. The drying step should not be confused with preliminary dewatering; this dewatering, usually by mechanical means, precedes the incineration process in most systems. A sludge, having a moisture content of about 75 percent is delivered to the most common types of incinerators. Since the typical sludge contains about 3 pounds of water for each pound of dry solids, the heat required to evaporate the water nearly balances the heat available from combustion of the dry solids.(65d)

B Drying and combustion may be done in separate pieces of equipment or successively in the same unit. Manufacturers have developed widely varying types of sludge drying and combustion equipment. These include traveling-grate furnaces, rotary-kiln-type furnaces, fluidized-bed units, wet-oxidation units, atomized spray units, multiple hearth furnaces, and flash-drying units.

Table 19. 1

Material	Combustibles (%)	Ash (%)	Btu/Pound
Grease and scum	88.5	11.5	16,750
Raw sewage solids	74.0	26.0	10,285
Fine screenings	86.4	13.6	8,990
Ground garbage	84.8	15.2	8,245
Digested sewage solids and ground garbage	49.6	50.4	8,020
Digested sludge	59.6	40.4	5,290
Grit	33.2	69.8	4,000

The drying and combustion process consists of the following phases: (1) raising the temperature of the feed sludge to 212°F, (2) evaporating water from the sludge, (3) increasing the water vapor and air temperature of the gas, and (4) increasing the temperature of the dried sludge volatiles to the ignition point.(65d)

C Practical operation of an incinerator requires that air in excess of theoretical requirements must be supplied for complete combustion of the fuel. The introduction of excess air has the effect of reducing the burning temperature and increasing the heat losses from the furnace. For this reason, a closely controlled minimum excess air flow is desirable for maximum thermal economy. The amount of excess air required varies with the type of burning equipment, the nature of the sludge to be burned, and the disposition of the stack gases.

D Fuel (sludge) burned in a furnace emits heat; some is absorbed by the furnace and is lost by radiation, a larger portion is lost with the stack gases, and a smaller portion is lost with the ash. The difference between the heat generated and the heat lost is available for heating the incoming sludge and air. Self-sustained combustion is often possible with dewatered raw sludges once the burning of auxiliary fuel raises incinerator temperatures to the ignition point.

E The primary end products of combustion are considered to be water, sulfur dioxide, carbon dioxide, and inert ash.

III TYPES OF FURNACE

In general, there are only three types of furnace capable of burning sewage sludge, including conditioned sludge resulting from the biological treatment of trade effluents. These are (a) the rotary drum furnace, (b) the fluidized-bed furnace, and (c) the multiple-hearth furnace.

A Rotary Drum Furnace (Figure 1)

This consists of an inclined cylinder with internal baffles which is rotated slowly by a toothed gear ring enshrouding the barrel. Sludge is admitted at the upper end and normally travels with the flow of heated combustion air. Ash and flue gases are discharged from the lower end of the drum and the exhaust gases contain about 20 per cent by weight of the ash. Because of structural difficulties in providing firebrick insulation inside the drum, the heat losses are high, which means that a well-dried cake must be produced by the preceding dewatering process in order to achieve autothermic incineration. In this state, no extraneous fuel is needed except for part-load operation or during startup.

B Fluidized-bed Furnace (Figure 2)

Fluidized-bed techniques have produced a compact form of furnace suitable for burning any material which can satisfactorily be fed to it, including sewage sludge. The bed of specially selected silica sand is maintained in a highly turbulent state by the combustion air and both the sludge and any supplementary fuel are fed directly into this zone. Combustion is completed in one or two seconds at a temperature of about 950°C.

Table 1

Effect of Moisture Level of Sludge on Auxiliary Fuel Requirement*

Per Cent Solids Wet Basis	Moisture Content Dry Basis (lb. water/lb. dry solid)	Auxiliary Heat Required (Btu/lb. dry solid)	Additional Cost ($/ton dry solid)
15	5.67	5830	5.8
20	4.0	2500	2.5
25	3.0	500	0.5
30	3.33	-833	-
35	1.85	-1780	-
40	1.5	-2500	-

*Calculation is based on sludge with heating value of 5500 Btu/lb. of dry solids. Heating requirement is estimated from water content only, using 2,000 Btu/lb. of water. Fuel is estimated to cost $0.50/million Btu.

With this type of furnace all the ash appears in the flue gases so that highly efficient gas cleaning is essential to maintain statutory requirements for gaseous discharges. Furthermore, it is necessary to incorporate a recuperative heat exchanger to pre-heat part or all of the combustible air. Since this exchanger has to handle flue gases at between 900°C and 1000°C, it is by no means cheap. It is not, therefore, economically justifiable to reduce the temperature of the exit flue gases below 700°C, which inevitably results in a poorer overall heat balance than that of the multiple-hearth incinerator.

The principal application of this type of furnace is for burning sludges with a significant content of highly volatile material such as those resulting from the treatment of oil refinery or chemical plant wastes. Its "all-up" cost is about the same as that of a multiple-hearth furnace installation for the same duty. However, it is not possible at present to build a fluidized-bed furnace with a capacity as large as that of the biggest multiple-hearth furnace, the chief obstacle being the difficulty of feeding the cake uniformly over the whole of the bed.

C Multiple-hearth Furnace (Figures 3 and 4)

This furnace consists essentially of a firebrick-lined, vertical, cylindrical shell with firebrick diaphragms or hearths set one above the other. Alternate hearths are centrally or peripherally perforated to permit the simultaneous downward flow of burning material and upward flow of burning material and upward flow of combustion gases in true counter-current fashion. A central, hollow, air-cooled rotor is fitted with air-cooled, radial, hollow rabble arms and rabble teeth and this rotates slowly about the vertical axis. This ensures that all the solids passing through the furnace are continuously raked to facilitate even combustion. Because of the counter-current flow of solids and gases, automatic pre-heating of the combustion air takes place without the need for flue gas heat exchangers. Since only about 10 per cent by weight of the ash left by combustion appears in the flue gases, much less elaborate cleaning is necessary than with the fluidized-bed furnace.

1 Furnaces of up to 7 m (roughly 23 ft.) internal diameter can be built and from four to twelve hearths are normally specified according to the duty involved. Exit gas temperatures of between 300°C and 600°C are achieved, depending on the nature of the sludge being burned.

2 Because of a phenomenon known as "thermal jump," sewage sludge being burnt in a multiple-hearth furnace exists for only a very short time in the distillation range of temperatures in which offensive-smelling vapours are generated. Although the gas phase goes through a steady temperature reduction in its upward passage through

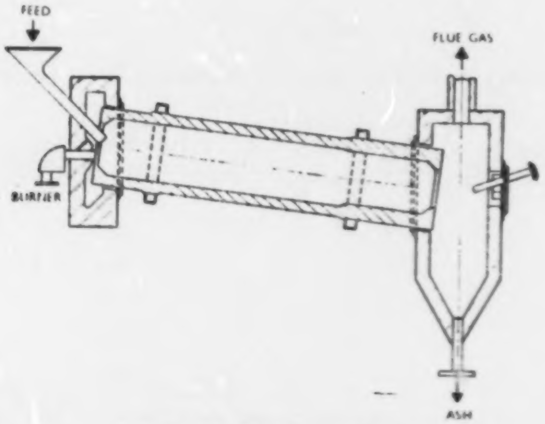
FEED
FLUE GAS
BURNER
ASH

Fig. 1. Diagram of rotary furnace

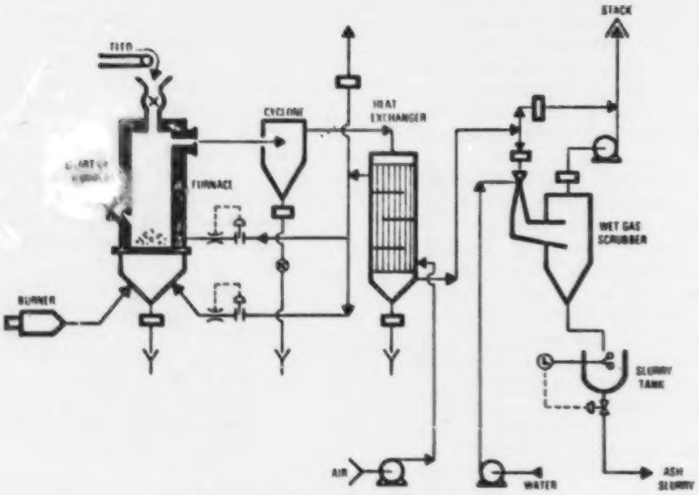
FEED
START UP BURNER
FURNACE
CYCLONE
HEAT EXCHANGER
STACK
WET GAS SCRUBBER
SLURRY TANK
BURNER
AIR
WATER
ASH SLURRY

Fig. 2. Flowsheet of fluidized bed furnace

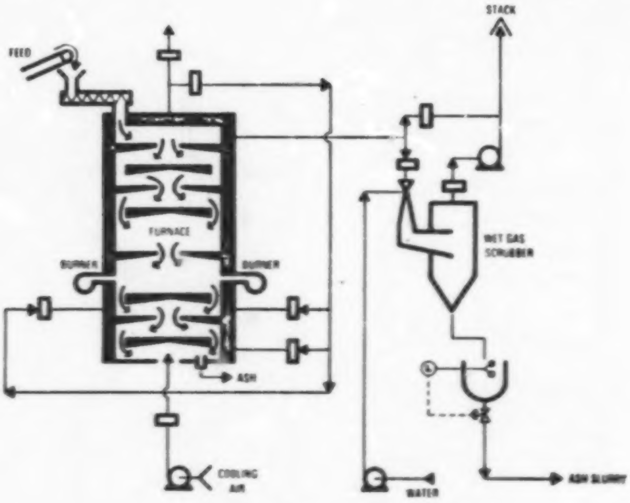

Fig. 3. Flowsheet of multiple-hearth furnace

the furnace, the descending sludge remains for most of its drying period at about 90°C because of the presence of water in the liquid phase. In the combustion zone the temperature rises rapidly to between 800°C and 900°C and essentially complete combustion takes place. The ash is normally characterized by an ignition loss at 800°C of less than 1 per cent by weight. It is odourless and sterile. Wetter sludges can be burnt more econonically in a multiple-hearth furnace than in a rotary or a fluidized-bed furnace. Autothermic incineration can be achieved with undigested primary sludge containing about 30 per cent dry solids whereas approximately 40 per cent solids would be needed in a fluidized-bed furnace.

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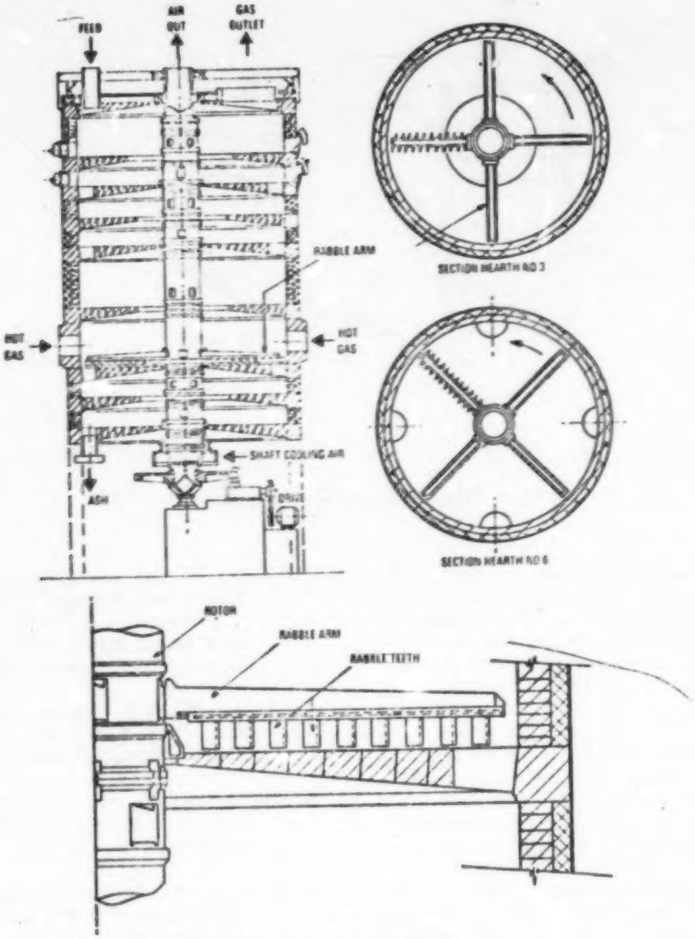
FEED
AIR OUT
GAS OUTLET
RABBLE ARM
HOT GAS
HOT GAS
SHAFT COOLING AIR
ASH
DRIVE
SECTION HEARTH NO 3
SECTION HEARTH NO 6
ROTOR
RABBLE ARM
RABBLE TEETH

Fig. 4. Multiple-hearth furnace

ULTIMATE DISPOSAL TO THE ENVIRONMENT

I INTRODUCTION

A Pollutants removed from wastewaters must be treated in such a way that they will not pollute the environment.

1 A pollutant is a substance that interferes with the intended use of the environment.

2 Incineration to reduce volume of organic wastes must not lead to air pollution.

3 Likewise, the effluent from a scrubber used to control air pollution from a furnace must be treated to prevent water pollution.

4 Seven places to put wastes. Outer space, air, oceans, fresh water, underground, land surface reuse.

5 Pollutant substances must be rendered innocuous either by dilution below background level or by locking up in precipitates.

B Disposal to Air and Outer Space

1 Water vapor and CO_2.

2 Heat. Thermal pollution kills fish by direct action, reduction of DO, interference with reproduction and increased susceptibility to disease.

C Ocean Disposal - Lowest Cost for Coastal Cities

1 Potential danger to environment.

2 Floatable and settleable solids are not well diluted.

3 Food chains may concentrate poisons killing larger species.

4 Barge to deep water and sink to bottom.

5 Ocean pipeline to deep water and sink solids. West Coast.

6 Ocean diffuser into well mixed area. Gulf and East Coast Continental Shelf. Sludge beds may suffocate bottom organisms.

D Land Disposal. Fill or Dump.

1 Lowest cost for small plants.

2 Not suitable for soluble substances such as salts.

3 Needs dewatering to produce solid that will bear a load. Useful for insoluble inorganic wastes.

4 Organics will putrefy and decay and may produce foul seepage and subsidence of the surface.

E Land Disposal. Surface spreading and Plowing in.

1 Not suitable for solubles except nutrients in quantities utilized by plants.

2 Low cost dewatering; can handle liquid sludges.

3 Low cost oxidation of organic matter.

4 Many elements locked up on soil minerals.

5 Improves soil for agriculture and forestry.

6 Suitable for small or large plants. Chicago uses train, barge and pipeline.

F Land Disposal. Wells.

1 Wells into porous formations are unsuitable for sludges or liquids containing filterable solids.

2 Useful for salt disposal into saline aquifers.

3 May leak out and contaminate other waters.

4 Large volumes may produce earthquakes and land movement.

G Polluting Substances

Consider pollutants on an element-by-element basis. Fortunately do not have 101 problems as most elements will not be pollutants.

II ORGANIC SUBSTANCES

A Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, Sulfur, Ash.

B Principal problem in disposal of organic sludges in water. Twenty to fifty times as much water as all other substances in waste.

C Carbon and hydrogen in organic compounds can be oxidized to CO_2 and H_2O which do not pollute the atmosphere. Avoid CO and odor by proper furnace operation.

D Heat Production

1 Oxidation of 1 lb of organic sludges is sufficient to evaporate about 2 lbs of water. Up to 3 lbs for oily sludge since combined O as in carbohydrates reduces heating value.

2 High temperature oxidation uses all the heat of combustion to evaporate water left in the sludge and usually requires excess fuel.

3 Economics of incineration are therefore closely tied to dewatering by sedimentation, filtration, and drying.

E Treatment of Wet Sludge to Aid Further Processing

1 Anaerobic digestion. Reduces solids about 50% by hydrolysis and fermentation to methane gas which is burned to CO_2 and water. Produces foul supernatant liquor which returns organics and nutrients to the plant for recycle.

2 Sludge cooking at 370° F. Porteous Process improves filterability of solids. Returns 10-20% of the BOD and 60-80% of the nitrogen.

3 Wet oxidation - Zimpro at 350° F removes 15% of COD by oxidation; dissolves 25% of solids and 90% of nitrogen. Higher temperatures destroy more solids. Improves filtration, produces a foul supernatant liquor.

4 Aerobic stabilization. Aerate for 1-15 days. Stabilizes solids but does not aid dewatering. Nitrates can be destroyed and phosphates held in solids.

F Oxidation and dewatering on land surfaces. An "old-fashioned" process.

1 Organics are oxidized by soil bacteria.

2 Nutrients and other pollutants are fixed to a significant extent and kept out of water supplies.

3 Must control putrefaction and spread of pathogens by pretreatment.

III PHOSPHORUS

A Composition and Occurrence

1 Sewage contains orthophosphate, polyphosphate and organic phosphates. Total P in secondary effluent averages near 8 mg/l as P (24 as PO_4, 18 as P_2O_5), large fluctuations with place and time.

2 Biological treatment, which may begin in the sewers, hydrolyzes up to 90% of the phosphates to ortho- as HPO_4 in secondary effluent.

B Organic sludges carry a fraction of the total P load.

1 Anaerobic digestion normally returns a large fraction of the P to the plant.

2 Combustion retains P in ash.

3 Land spreading fixes P on soil minerals but silt carries P into streams.

C Lime Sludges

1 High pH precipitates calcium phosphate as $Ca_5OH\ (PO_4)_3$, hydroxyapatite. This is frequently referred to and calculated as tricalcium phosphate or "tri cal," $Ca_3(PO_4)_2$, which is called bone phosphate of lime, bpl, in Rock Phosphate analyses.

2 Lime dosage of up to 600 mg/l as $Ca(OH)_2$, (450 as Cao) has been used to raise pH above 11 and precipitate calcium phosphate in tertiary treatment.

3 Tertiary lime sludge can be dewatered easily by sedimentation and vacuum filtration or centrifugation to 25-40% solids.

4 Burning in a lime kiln or incinerator converts $CaCO_3$ to CaO. Calcium phosphate is essentially unchanged.

5 CaO can be slaked to $Ca(OH)_2$ which can be reused. Calcium phosphate remains with inerts including MgO which does not slake.

6 High phosphate sludge has low solubility in water and can be safely dumped. May have market value as fertilizer since P is available to growing plants.

7 Recovered lime costs nearly as much as new lime but partially solves disposal problem. Lake Tahoe, California.

8 Lime treatment of primary reduces BOD, SS, and phosphates (Dorr-Oliver). Sludge may be hard to dry on sand beds but does not putrefy.

D Alum Sludges

1 Aluminum salts hydrolyze to aluminum hydroxide and precipitate phosphates near pH 7.

2 Aluminum to phosphate ratio close to 2:1. $AlPO_4 \cdot Al(OH)_3$ probably not a pure compound.

3 Disposal of aluminum hydroxide sludges rich in organic matter may be difficult. Aluminum phosphates are not dissolved in anaerobic digesters but sludges are hard to thicken. Lime improves dewaterability.

E Iron Salts

1 Hydrolyze (and oxidize) to produce ferric hydroxide $Fe(OH)_3$ which removes phosphates as basic ferric phosphate.

2 Ferric phosphate $FePO_4$ reduced in digesters to ferrous phosphate $Fe_2(PO_4)_3$. Insoluble but dissociated by H_2S to form FeS which may liberate soluble phosphates.

3 Possible utility when acid mine wastes or iron pickle liquor is available. No recovery of iron.

IV NITROGEN

A All nitrogen comes from the air and ultimately returns to the air.

1 All forms of N are biologically interconvertible. Report all forms of nitrogen as mg/l N.

2 All except N_2 are pollutants. "Good" fertilizers in water.

B Organic Nitrogen

1 Burn to N_2 gas with some oxides of nitrogen if furnace design is inadequate.

2 Hydrolyze to NH_3 by anaerobic or short time aerobic treatment.

3 Oxidize to nitrate with long time aeration in presence of suitable bacteria.

C Inorganic Nitrogen

1 Ammonia as a pollutant above 1 mg/l in municipal or surface waters. Not an air pollutant but could be reabsorbed in waters.

2 Chlorine destroys ammonia producing N_2 but requires 10 parts of Cl_2 per part of NH_3-N.

3 Soils adsorb ammonia. Bacteria in soil convert excess to soluble nitrates. Growing plants need NH_4^+ or NO_3^-.

4 Nitrates are denitrified by growing bacteria at low oxygen levels supplying O_2 and liberating N_2. Denitrification occurs in soils and can be done in packed beds or tanks if food such as methanol is supplied.

V SALTS IN SOLUTION

A Na^+, K^+, Ca^{++}, Mg^{++}, salts of Cl^-, HCO_3^-, HCO_2^-, $SO_4^=$

1 Soluble. No good precipitant.

2 No economical sale.

3 Illegal to discharge on surface in some arid areas including Texas.

4 Solar evaporation to solid to reduce transportation costs.

B Dilute in sea water or salt lakes.

1 Discharge to rivers on spring floods has been practiced.

C Inject into underground cavities or saline aquifers.

D Concentrated salts from Reverse Osmosis, Electrodialysis, Ion Exchange.

1 Scale forming if concentrated 10-fold, i.e., 90% water recovery.

VI TRACE ELEMENTS, POISONOUS IN EXCESS

A Lime clarification will remove Ca, Mg, Sr, Ba, Al, Cr^{+3}, Mn, Fe^{+3}, Co, Ni, Cu by precipitation. May also remove Zn, Cd, Hg, As, Sn, Sb, and Pb by adsorption.

B Hg, Cd, and Zn strongly adsorbed on organics but are volatile and may be lost in flue gases. Hg converted to methyl mercury in lake bottom muds.

C Heavy Metals, Cyanides, Selenium, Arsenic, and some other poisons can be kept out of wastewater more economically than they can be removed.

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